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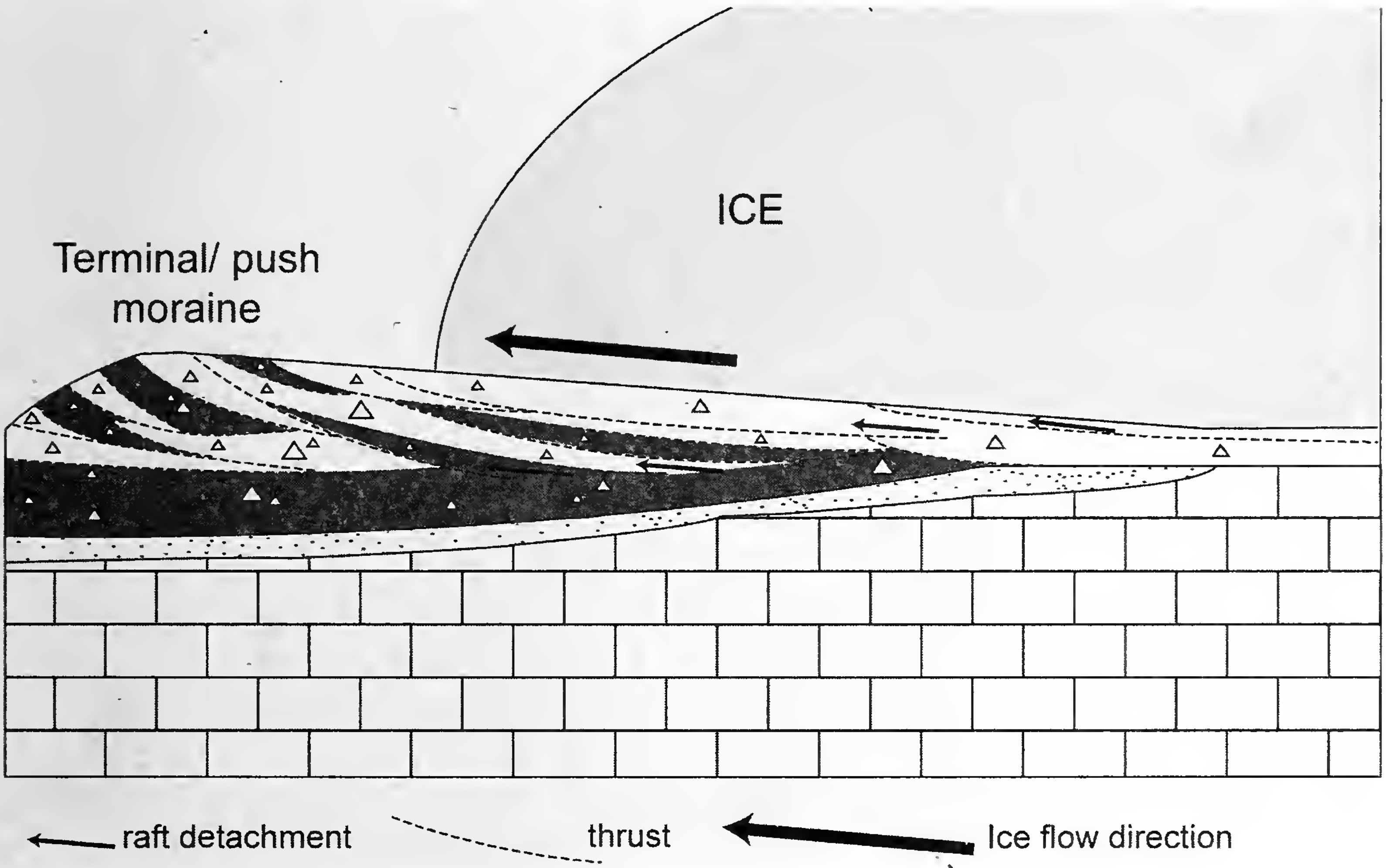

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Tills, Weybourne Town Pit, Norfolk

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EDITORIAL

This issue of the Bulletin concentrates on East Anglia's famous Pleistocene glacial tills. There has been much renewed research effort on these deposits in the last two decades and it may amaze some that there are still new observations and interpretations to be made. Of course this is what makes our science so exciting and vibrant, not least when debate ensues. The paper by Langford examines the Lowestoft Till in the Peterborough area. The approach is to compare magnetic properties of the glacial sediments with those already known for Norfolk and Suffolk. The results do not support uniformity of source sediment entrained in the ice which may further challenge some models for Lowestoft Till ice flow. The paper by Evans and others is a detailed re-analysis of the glaci-tectonized tills exposed in Weyboune Town Pit, north Norfolk. The authors use sedimentological, palynological and structural analysis to conclude that these sub glacial tills underwent brittle deformation resulting in thrusting soon after initial deposition. The deformation is interpreted to have been driven by oscillation of an ice margin, the 'push' coming from a northerly direction

Copy for Bulletin 62 is now being assembled and I hope it will be published in the first half of 2012.

INSTRUCTIONS TO AUTHORS

Contributors should normally submit manuscripts either as word-processor electronic files (MS Word is preferred) or hard copy. When papers are accepted for publication we will request an updated electronic version.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation etc. conforms as strictly as possible to that used in Vol. 53 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

We hope to make pdf versions of all papers from now on to serve as offprints for authors and for possible future WWW availability. For this reason we prefer illustrations drawn with a computer graphics package, ideally saved in jpeg format. Thick lines, close stipple or patches of solid black or grey should be used with care as they can spread in printing hard copy. The editor may have diagrams re-drawn professionally and usually the GSN will cover the cost of this. For efficient use of space full use should be made of the width of print on an A4 page when designing diagrams. Half tone photographic plates (if possible reproduced as jpeg files) are acceptable provided the originals exhibit good contrast.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

NEW SEDIMENT MAGNETIC DATA FROM ANGLIAN (MIDDLE PLEISTOCENE) GLACIAL DEPOSITS IN THE PETERBOROUGH AREA: A COMPARISON WITH DATA FROM NORFOLK AND SUFFOLK

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ABSTRACT

Sediment magnetic properties of Lowestoft Till (Anglian/Elsterian/marine oxygen isotope stage 12) outcrops in Norfolk and Suffolk were compared with those from the Peterborough area, eastern England. Lowestoft Till does not crop out contiguously in East Anglia, and in the past separate outcrops have been correlated by their lithological properties. Sediment magnetic properties of separate Lowestoft Till outcrops might therefore be expected to be similar. In this instance the 63–250 μm non-carbonate fraction was used for the determination of magnetic properties because previous research had suggested that the lithological properties of part of this component might be characteristic of Lowestoft Till, with a source area in the North Sea. It is shown here that the analysed fraction of Lowestoft Till outcrops in Norfolk and Suffolk have high concentrations of magnetic minerals with a characteristic component of 'soft' magnetic grains, whereas the samples from the Peterborough area, excluding Ketton, have high concentrations of magnetic minerals with a characteristic component of 'hard' magnetic grains. The Lowestoft Till at Ketton has low concentrations of magnetic minerals with a characteristic component of 'hard' magnetic grains. The magnetic-grain assemblages from the two areas being compared thus represent not two but three different populations. This finding has implications for the rather simplified notions about Lowestoftian ice flowpaths and thus the perceived Anglian ice limits.

Bull. geol. Soc. Norfolk (for 2011), **61**, 3-22.

INTRODUCTION

This article compares sediment magnetic properties of Anglian/Elsterian (marine oxygen isotope stage (MIS) 12) glacial deposits (Lowestoft Till – cf. Mitchell *et al.*, 1973; Bowen, 1999: Walcott Till/Second Cromer Till – cf. Hamblin *et al.*, 2005) in the Peterborough area (Fig. 1; henceforth the 'study area') with equivalent deposits in Norfolk and Suffolk (Corbett, 1996, 2001a, 2002). Analysis of terrigenous glacigenic sediments using sediment magnetic properties, however, is not common (e.g. Walden *et al.*, 1987, 1992, 1995; Corbett 1996, 2001a,b, 2002; Andrews *et al.*, 2002). Walden *et al.* (1987, 1992, 1995) used a suite of magnetic properties measured on a range of grain-size fractions below 1 mm and on individual clasts to characterize different Devensian/Weichselian (MIS 2) tills. Corbett (1996, 2001a, 2002) applied cluster analysis to a range of magnetic variables measured on the non-carbonate 63–250 μm grain-size fraction of chalk-rich diamictons in combination with lithological variables in order to differentiate Anglian/Elsterian tills (Lowestoft Formation and North Sea Drift tills) on what he termed the 'Chalky Boulderclay Plateau' of Norfolk and Suffolk (Fig. 1).

Lowestoft Till does not form a contiguous deposit either in East Anglia generally, or in the study area. Correlation between outcrops relies on their lithological properties (Mitchell *et al.*, 1973; Perrin *et al.*, 1973, 1979; Allen *et al.*, 1991; Ehlers and Gibbard, 1991; Ehlers *et al.*, 1991; Rose, 1994, 2009; Bowen, 1999; Clayton, 2000; Hamblin *et al.*, 2000, 2005; Clark *et al.*, 2004). Present understanding of Lowestoftian ice flowpaths and Anglian ice limits is still largely reliant on Perrin *et al.* (1973, 1979), although the regional-scale study by Corbett (1996, 2001a, 2002) raises some questions about their conclusions. Corbett reported that stratigraphical grouping according to the lithological variables he used was not viable, because no coherent lateral or vertical distribution patterns were discerned from the combined statistical analyses of his measured variables data set (450 samples from 26 sites; Corbett, 2001a). Corbett's important findings, however, have generally been ignored in the more recent literature (e.g. Rose, 2009).

Composition of Lowestoft Till does vary laterally according to variation in substrate materials (e.g. Allen *et al.*, 1991; Corbett, 2001; Rose, 2009), but there is considered to be a common core component. Perrin *et al.* (1973) noted the persistent presence of a non-carbonate sand fraction in Lowestoft Till, and as the heavy mineral component of the 63–105 μm fraction was similar for both the Lowestoft Till and North Sea Drift, they suggested that the source of this sand fraction was the floor of the North

Sea. Corbett (1996) therefore chose the non-carbonate 63–250 μm grain-size fraction for the analysis of sediment magnetic properties. A working hypothesis therefore can be proposed that the silt to fine sand component of samples from Lowestoft Till outcrops in the study area should have similar magnetic properties to outcrops in Norfolk and Suffolk because they have a common North Sea source; the null hypothesis being that the magnetic properties will be different because deposits classified as Lowestoft Till do not share a common source.

As an extension to his study of the glacigenic sediments in Norfolk and Suffolk (Corbett, 1996), W. M. Corbett collected samples from exposed sections in Lowestoft Till (Horton, 1989; Davey, 1991; Maddy, 1999) at March, Stanground and Ketton in the study area (Fig. 1). In addition Langford (HEL) supplied samples from exposed sections in Lowestoft Till (Horton, 1989; Davey, 1991; Maddy, 1999) at Chesterton Hill, Alconbury and Stanground (Fig. 1). Samples were collected from freshly exposed faces, well below the present soil horizon in order to minimize pedogenic effects. All samples were analysed by W. M. Corbett following the procedures detailed in Corbett (1996, 2001a, 2002), and, with the exception of the Ketton data, the lithological and magnetic-variable data were provided to the author for his investigation of Middle Pleistocene deposits of the Peterborough area (Langford, 1999).

Full details of the methods used for data collection and presentation and statistical treatment can be found in Corbett (1996, 2001a, 2002), and are not repeated here. W. M. Corbett also supplied lithological data for each of the samples from the area, and for completeness these data are provided in the Appendix.

SAMPLE SITES IN THE STUDY AREA

At Stanground (TL 202 955; Fig. 1) the surface height is 16.33 m OD and the base of the sequence is at about –5 m OD. Three samples were collected by W. M. Corbett from Stanground in June 1997: CRD4a from 3 m below the surface, CRD4b 5 m below the surface and NCRS1a from a lacustrine deep-water facies 6 m below the surface – the prefix CRD denotes samples from chalk-rich diamictons, whereas those prefixed by NCRS are from penecontemporaneous non-chalk-rich substrate sediments. Samples NCRS1a and b were collected by HEL from a lacustrine deltaic facies at Stanground in 1993: both from depth > 10 m below the present surface. Samples CRD4c and d were collected by HEL from Alconbury (TL 183 796; Fig. 1) in June 1997: 3.5 m and 4 m

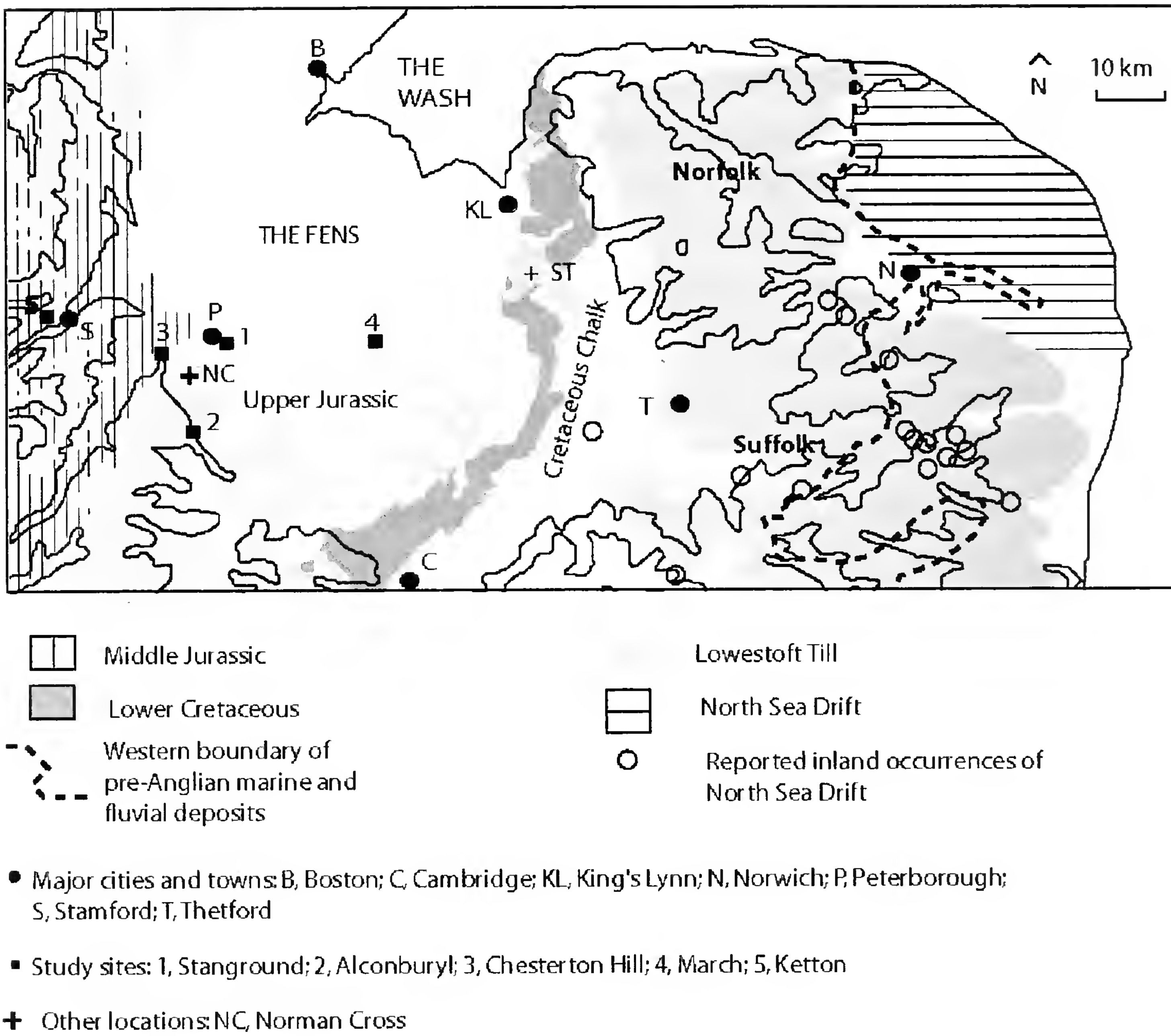

Fig. 1. Location of study sites, generalised bedrock and surficial geology of the study area, Norfolk and north Suffolk, and 50 and 100 m contours. To aid clarity post-Anglian (marine oxygen isotope stage 12) deposits are not shown. (Compiled from Langford, 1999; Whiteman and Lewis, 2000; Corbett, 2002.)

below the present surface respectively; sample CRD4c is from a chalk-rich pocket within the chalk-rich diamicton.

Two chalk-rich, matrix-supported diamictons are present, in superposition, at Chesterton Hill (TL 132 934; Fig. 1), corresponding to the sequence reported by Fish and Whiteman (2001). They appear to be restricted to above 40 m OD. Samples CRD1 and CRD2 were collected in May 1990 by HEL: 5 m and 3.5 m below the present surface (about 50 m OD) respectively.

At March (TL 990 405; Fig. 1) the sedimentary succession is > 23 m thick, with its base at more than 18 m below present sea-level, and it appears to infill a north–south trending buried channel feature (Langford and Boreham 1998). Samples CRD3a and b were collected by W. M. Corbett in June 1997 from 3 and 5 m below the surface respectively. Samples NCRS3a and b were collected by HEL in February 1998 from the upper part of a lacustrine deltaic facies > 7 m below the surface.

At Ketton (TF 985 063; Fig. 1) the chalk-rich diamicton was a little over 3 m thick and comprised interdigitating dark and light diamictons, The surface height is between 70 and 85 m OD. Samples CRD6a–c were collected at approximately 1.3, 1.6 and 1.9 m below the present-day surface.

RESULTS AND INTERPRETATION

The magnetic properties of samples from the study area are listed in Table 1 and plotted in Figures 3–5 alongside the data for Lowestoft Till outcrops in Norfolk and Suffolk (ratio cluster R6; Corbett's (1996, 2001a,b, 2002) Chalky Boulderclay facies). Magnetic remanence curve envelopes in Figure 3a demonstrate that the Lowestoft Till samples of the study area are characterised by a component of 'hard' magnetic grains not present in the Lowestoft Till of Norfolk and Suffolk, whereas the latter has a component of 'soft' magnetic grains not present in the samples from the study area – except for the uppermost sample at Ketton (Table 1). The terms 'hard' and 'soft' refer to magnetic mineral domains that are not easily reordered or overprinted when the sample is exposed to a new magnetic field and vice versa, respectively. Figure 3b indicates that the excess (i.e. the proportion of an envelope that lies outside those it is being compared with) 'hard' magnetic grain component in Lowestoft Till samples of the area could largely be derived from contemporaneous substrate material, and that there is a small excess 'soft' magnetic grain component in the Lowestoft Till samples that is not present in the contemporaneous substrate samples. This latter value though is 50% less than the mean value for the Lowestoft Till of Norfolk and Suffolk. Note that the envelope for the magnetic remanence curves of the Ketton samples is not included in Figure 3b, because data for contemporaneous substrate sediments are available only for March and Stanground. The substrate samples for March and Stanground are also reliable proxies for the local bedrock (Upper Jurassic), as indicated by 85% and 71% locally derived clasts at Stanground and March respectively (Langford, 1999; 2004a,b), and by comparison of the geochemistry of the contemporaneous substrate and bedrock, although

Table 1. Sediment magnetic properties for samples from the study area: CRD, chalk-rich dimictons; NCRS, non-chalk-rich (penecontemporaneous substrate) sediments (Data provided by W. M. Corbett)

Location	Sample number	% remanent magnetization after induced magnetic fields (mT) 10	40	100	300	1000	MAGDIFF (mT)	A1000 mT	MDF (mT)
March	NCRS3a	2.4	41.6	76.6	96.4	100	3.6	85.9	49
	NCRS3b	3.4	40.5	82.1	95.8	100	4.2	46.0	49
	CRD3a	4.4	48.8	72.5	83.1	100	16.9	78.9	43
	CRD3b	2.9	36.3	66.6	79.7	100	20.3	50.5	60
Stanground	NCRS1a	2.1	38.0	67.3	82.0	100	18.0	57.6	58
	NCRS1b	1.9	35.0	73.8	88.9	100	11.1	57.8	56
	NCRS2	2.7	31.9	57.8	75.2	100	24.8	41.7	76
	CRD4a	4.9	32.9	71.6	85.6	100	14.4	76.2	51
	CRD4b	3.6	37.0	69.0	83.2	100	16.8	67.0	59
Alconbury	CRD4c	4.6	51.2	81.1	92.4	100	7.6	85.8	38
	CRD4d	4.0	39.9	73.1	86.0	100	14.0	85.0	53
Chesterton Hill	CRD1	2.7	34.5	70.4	88.0	100	12.0	72.2	60
	CRD2	3.7	43.3	75.6	87.1	100	12.9	72.2	60
Ketton	CRD6a	16.0	35.6	62.3	83.5	100	16.5	28.9	65
	CRD6b	2.6	32.4	60.0	80.1	100	19.9	24.3	71
	CRD6c	3.8	26.4	53.2	76.6	100	23.4	24.1	88

there are increases in the ranges of MgO, CaO, Co and V and decreases in the ranges of Cr, Pb, S and Zn in the contemporaneous substrate sediments (Langford, 1999). There is, however, a small component of 'hard' magnetic grains present in the Lowestoft Till samples in Figure 3b that is not present in the substrate samples.

From all the data analysed, Corbett (see Andrews *et al.*, 2002) considered that MDF (median destructive field) and A1000 mT (saturation isothermal remanent magnetization, which is made absolute by taking into account the sample mass – Corbett, 1996, 2002) for the ratio-derived clusters (R clusters) were the most meaningful discriminatory variables (Fig. 4). The MDF value is a proxy for the amount of 'hard' (high MDF values) and 'soft' (low MDF values) magnetic grains present (Corbett, 2002). The A1000 mT value is a measure of the concentration of magnetic grains, such that a high value indicates that there is a greater concentration of them present in the sample (Corbett, 2002). It is evident from Figure 4 that these two magnetic variables clearly differentiate the Ketton Lowestoft Till from the remainder in the study area and the Lowestoft Till of Norfolk and Suffolk. The Ketton Lowestoft Till is characterized by a

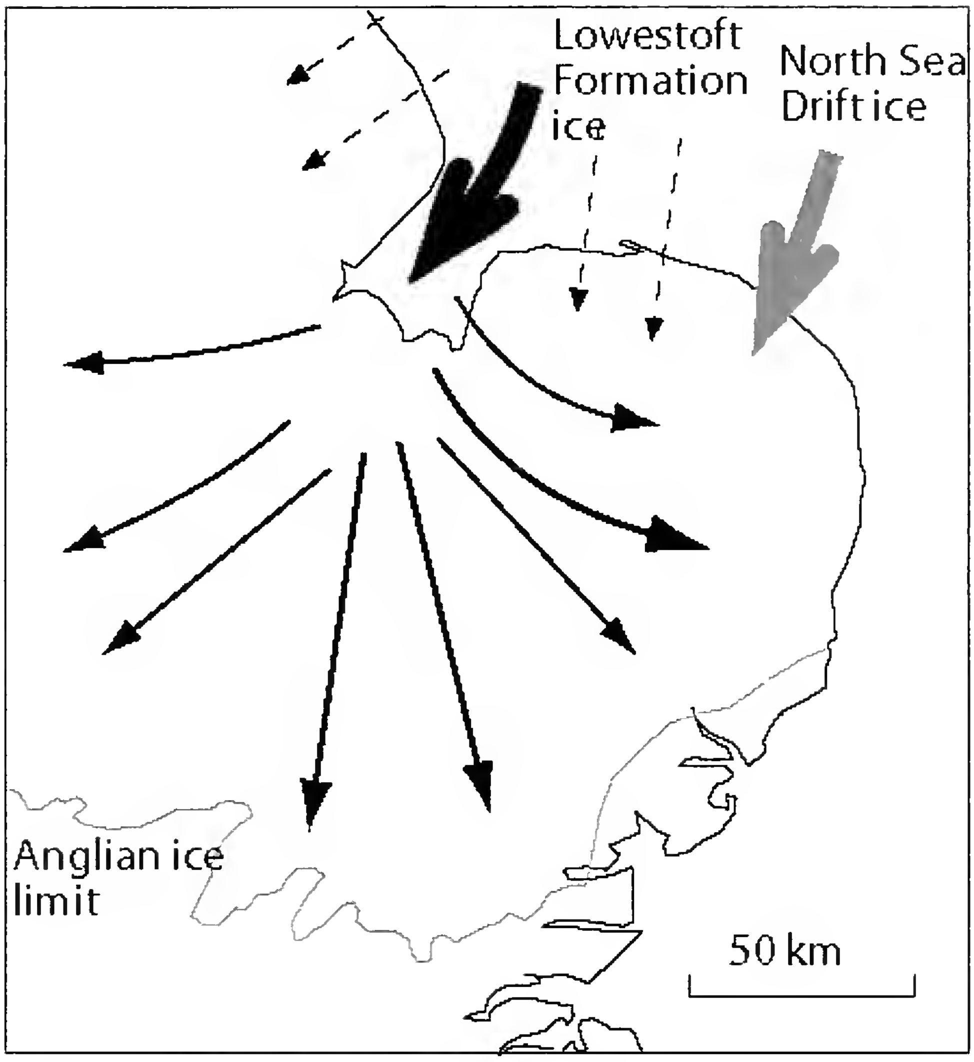

Fig. 2. The Lowestoftian ice advance as postulated by Perrin *et al.* (1979).

larger component of 'hard' magnetic grains (higher MDF value) and much lower concentrations (low A1000 mT values) of magnetic grains. Contemporaneous substrate samples and the remainder of the Lowestoft Till samples (FB – CRD) from the study area, on average, have a larger component of 'hard' magnetic grains. The substrate samples, on average, have lower concentrations than the Lowestoft Till samples (FB – CRD and R6), and the MDF values of the Lowestoft Till samples of the study area (FB – CRD) appear to be diluted because of their higher concentrations of magnetic grains.

Two other discriminatory variables are also used in this study (Fig. 5): MAGDIFF ('hard' isothermal remanent magnetization) and 10 mT ('softest' isothermal remanent magnetization). These are measures of the proportions of 'hard' and 'soft(est)' magnetic grains within a sample, respectively. Note that 10 mT was not used by Corbett (1996, 2001a, 2002) in the determination of R clusters. Although there is overlap in the values of these two magnetic variables between the FB – CRD, substrate and cluster R6 samples there is a clear tendency for those of the study area (FB – CRD and substrate) to have a larger component of 'hard' magnetic grains and a smaller component of 'soft'

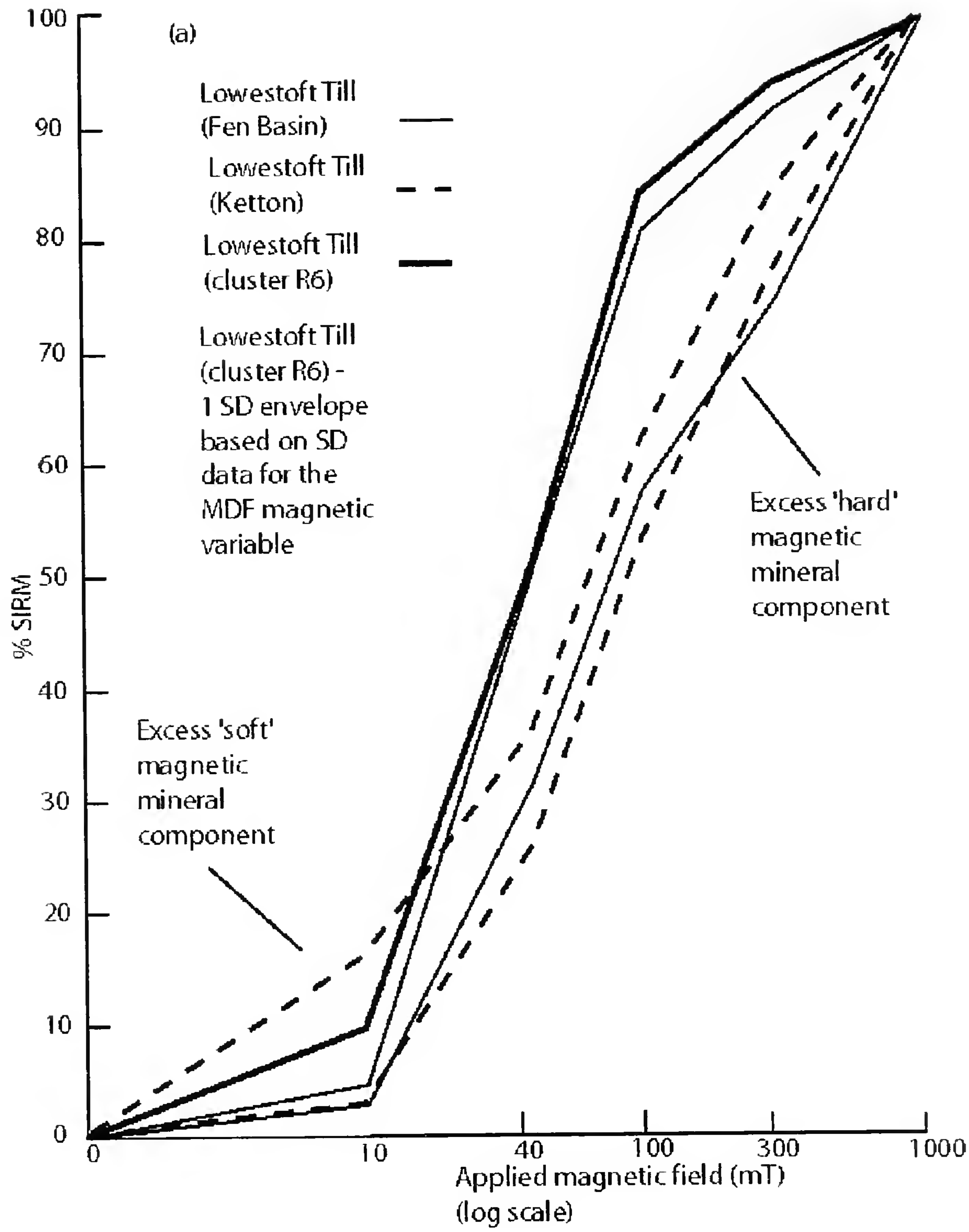

Fig. 3. (a) Comparison of the magnetic remanence curve envelopes for samples of Lowestoft Till from the study area (Fen Basin and Ketton) with the cluster R6 curve from Norfolk and Suffolk. In the absence of standard deviation (SD) data for cluster R6 the SD value for the median destructive field (MDF; ca. 10%; Corbett, 2002) of cluster R6 is shown.

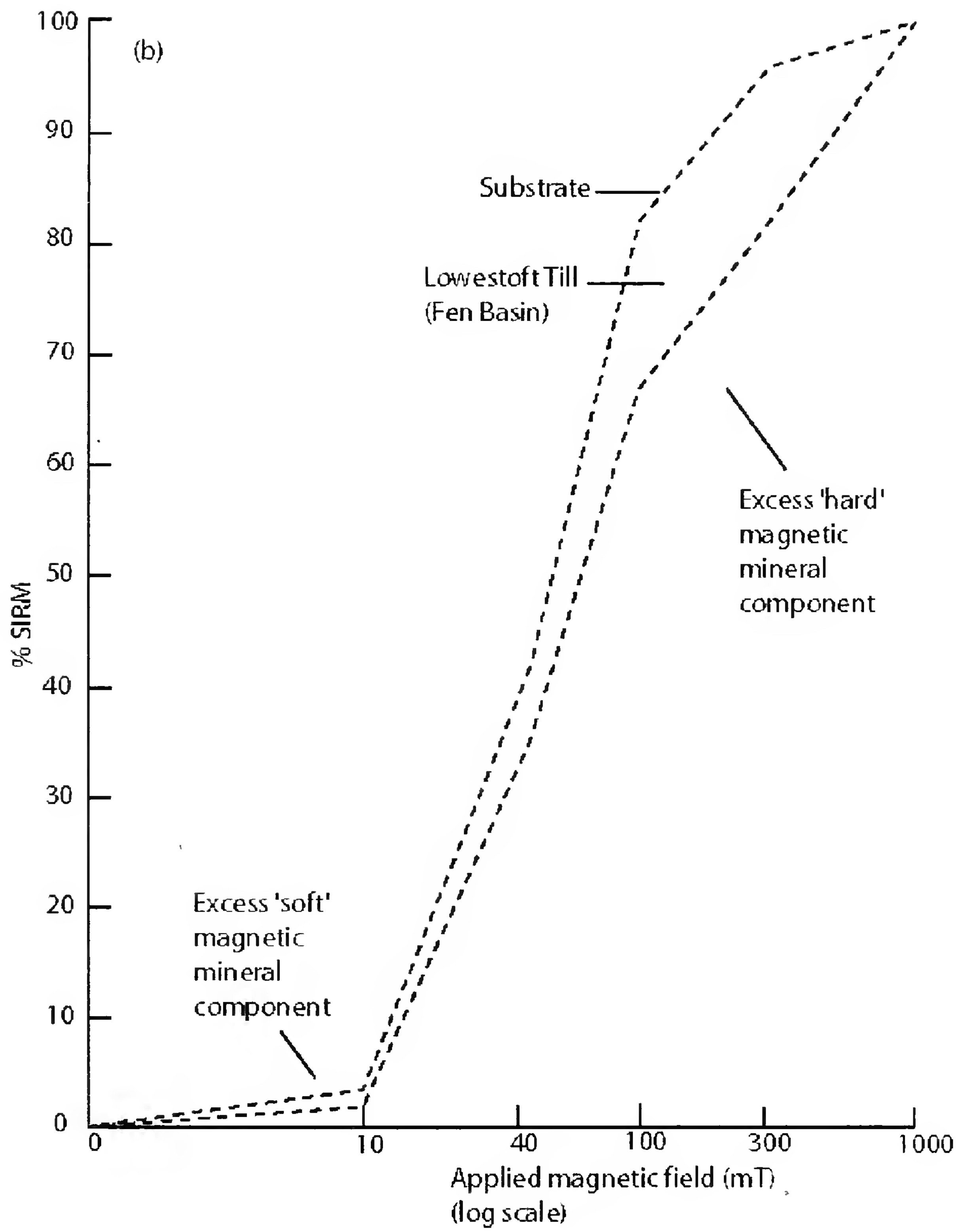

Fig. 3. (b) Comparison of the magnetic remanence curve envelopes for samples of Lowestoft Till of the Fen Basin (including Chesterton Hill but not Ketton – shaded area) and contemporaneous substrate sediments from March and Stanground – pecked line. (Data for the study area were provided by W. M. Corbett. Data for the R6 cluster are from Corbett 2002.)

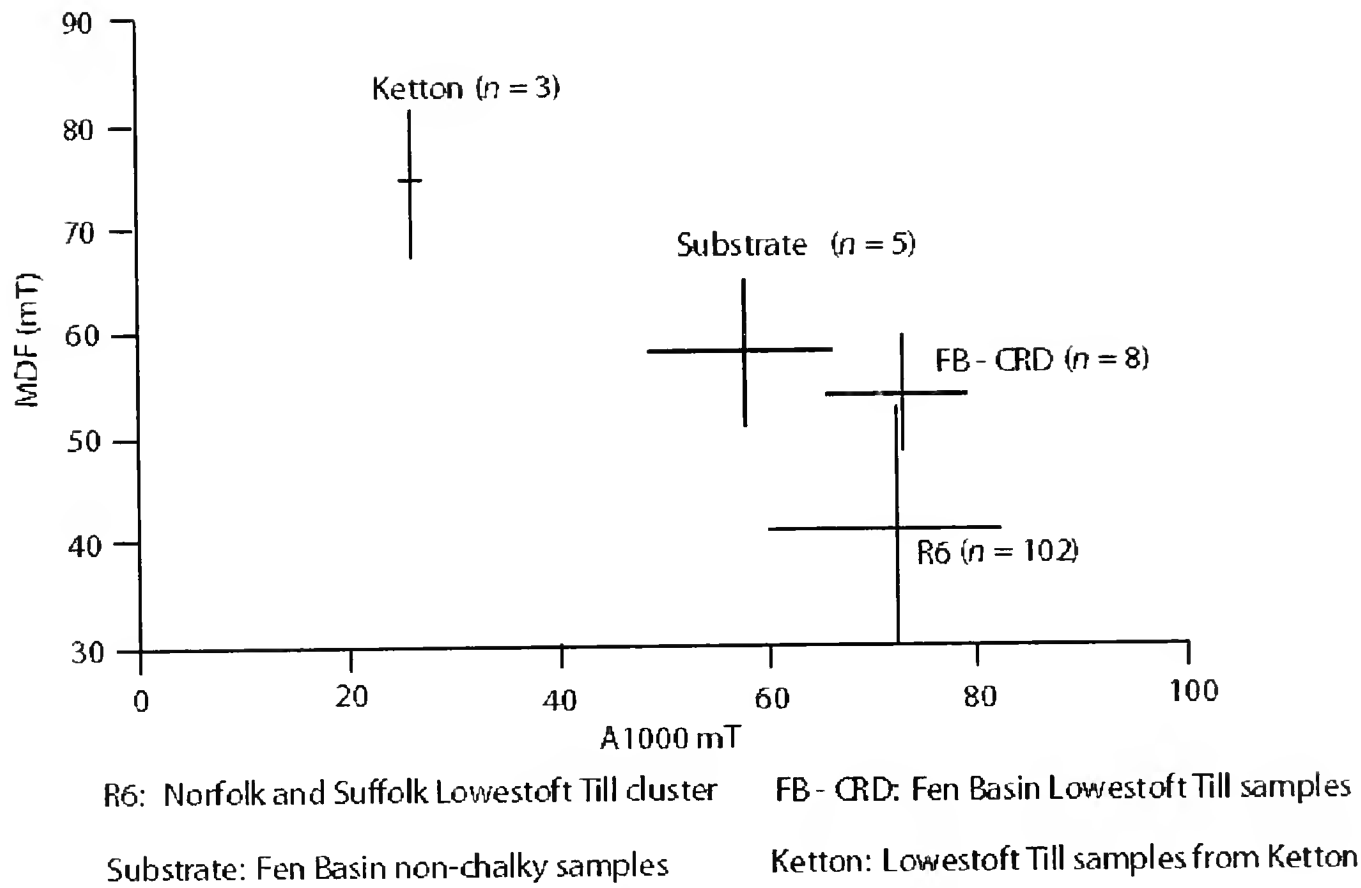

Fig. 4. Bivariate plot of MDF versus A1000 mT for Lowestoft Till and substrate samples from the study area compared with the plot for Lowestoft Till (cluster R6) from Norfolk and Suffolk. The 1σ standard deviation (SD) for ratio cluster R6 is shown. The mean and SD values for other data points were calculated using the statistics package in Microsoft Excel®. (Data for the study area were provided by W. M. Corbett. Data for the R6 cluster are from Corbett 2002.)

magnetic grains than the Lowestoft Till of Norfolk and Suffolk. As noted in Figure 3, there is a small component of 'hard' magnetic grains present in the FB – CRD samples not present in the substrate samples. Again the Ketton Lowestoft Till samples are clearly differentiated from all the other samples by their large component of 'hard' magnetic grains. Although there is a broad range of values for 10 mT, comparable with the Lowestoft Till of Norfolk and Suffolk, this is biased by the sample from the top of the sedimentary succession at Ketton. Unlike the Lowestoft Till samples from Norfolk and Suffolk though, the magnetic grains in the Ketton samples are present in low concentrations, suggesting that the source of 'soft' magnetic grains at Ketton is not related to the source in Norfolk and Suffolk, which is associated with high concentrations.

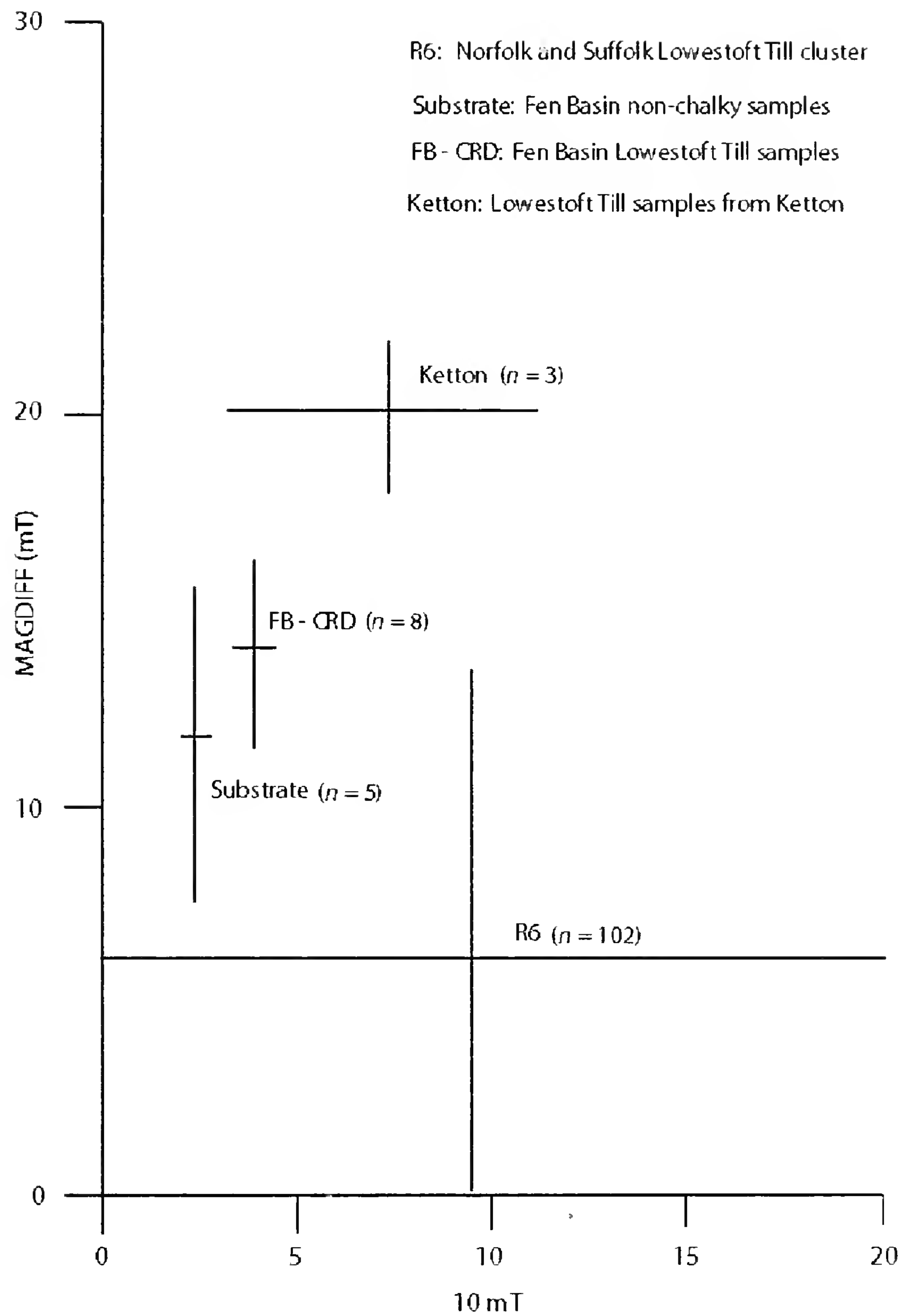

Fig. 5. Bivariate plot of 10 mT versus MAGDIFF for Lowestoft Till and substrate samples from the study area compared with the plot for Lowestoft Till (cluster R6) from Norfolk and Suffolk. The 1σ standard deviation (SD) of the MAGDIFF data for ratio cluster R6 is shown; that for 10 mT is not available but the 1σ SD for MDF is shown. The mean and SD values for other data points were calculated using the statistics package in Microsoft Excel®. (Data for the Fen Basin provided by W. M. Corbett. Data for the R6 cluster are from Corbett 2002.)

DISCUSSION

As Perrin *et al.* (1973) suggested that the 63–250 μm non-carbonate grain-size fraction could be an important characteristic of Anglian tills, sourced from the floor of the North Sea, Corbett (1996, 2002) investigated the magnetic-variable properties of this component, arguing that if this fraction was characteristic then these data would more faithfully represent the ice source region and/or ice-transport pathway. Four magnetic variables were used to compare the Lowestoft Till in the study area with ratio cluster R6, representing the Lowestoft Till (Chalky Boulderclay facies of Corbett, 2002) in Norfolk and Suffolk (Figures 3–5):

1 median magnetic field (MDF);
2 proportion of 'hard' magnetic grains (MAGDIFF);
3 concentration of magnetic grains (A1000 mT);
4 proportion of (very 'soft') magnetic grains that would be overprinted in an applied field of 10 mT.

It is apparent from Figures 4 and 5 that the Lowestoft Till samples of Ketton and those from the remainder of the study area (FB – CRD) form two distinctly separate groups, and on the basis of their sediment magnetic properties this makes correlation of them difficult to justify. The Ketton Lowestoft Till is distinctly different to the Lowestoft Till of Norfolk and Suffolk in terms of its much larger component of 'hard' magnetic grains. Although it shares a similar value for influx of 'soft' magnetic grains as the Lowestoft Till of Norfolk and Suffolk, the former has low concentrations whereas the latter has high concentrations of magnetic grains. It is therefore also difficult to justify correlation of the Lowestoft Till at Ketton with the Lowestoft Till of Norfolk and Suffolk on the basis of their sediment magnetic properties. However, as it is also demonstrated here that the difference in the amounts of the 'hard' magnetic grain component of the Lowestoft Till of the remainder of the study area (FB – CRD) and the Lowestoft Till of Norfolk and Suffolk could be largely due to incorporation of contemporaneous substrate material, it is possible that these outcrops of Lowestoft Till do correlate. However, there is a small component of 'hard' magnetic grains present in the FB – CRD samples that is not present in the R6 cluster samples, and a small component of 'soft' magnetic grains present in the Norfolk and Suffolk Lowestoft Till samples that is not present in the FB –

CRD samples: both of these features require explanation before any correlation can be supported.

Corbett (2002) attributed the characteristic component of 'soft' magnetic grains present in the Norfolk and Suffolk Lowestoft Till samples to a distant, up-glacier, igneous source, but this is difficult to envisage because such low-field magnetic grains are unstable (Maher and Hallam, 2005) and unlikely to survive the potential multiple recycling associated with glacial advance. It is possible that this 'soft' component of magnetic grains represents multidomain magnetite grains that are locked in the crystal structure of quartz grains in the silt to fine sand fraction used (cf. Maher and Hallam, 2005) for analysis of magnetic properties, but this is difficult to reconcile with the variable amounts and concentration patterns recorded in the data. If the silt to fine sand component analysed is considered to be a distinguishing characteristic of Lowestoft Till, with an up-glacier igneous source, then the component of 'soft' magnetic grains should be roughly equally distributed (cf. Walden *et al.*, 1995; Kjær, 1999) between disparate outcrops; especially if, as in the Lowestoft Till samples from Norfolk and Suffolk, it is present in high concentrations. This characteristic component of 'soft' magnetic grains present in the Norfolk and Suffolk Lowestoft Till samples is therefore more likely to be sourced from a local, pervasive, non-igneous source, for which data are at present not available.

CONCLUSIONS

The results of this study do not support the research hypothesis that the sediment magnetic data for the 63–250 μm non-carbonate grain-size fraction will be similar in samples of Lowestoft Till from outcrops in both the study area and in Norfolk and Suffolk. On the contrary, the magnetic-grain assemblages from the study area represent two different populations, and that from Norfolk and Suffolk yet another different population. This disparity in the sediment magnetic data between Lowestoft Till samples from different outcrops appears to challenge the central tenet of models proposing Lowestoftian ice advance through what is now The Wash and simply spreading radially westwards, southwards and eastwards (Perrin *et al.*, 1979; Rose, 1994, 2009; Clayton, 2000), scouring out the 'Fen Basin' and depositing the eroded sediments in Norfolk and Suffolk (Clayton, 2000). Rather, the data presented here supports work by Fish and Whiteman (2001) who concluded, on the basis of the distribution of Cretaceous Chalk microfossils in Lowestoft Till, that such models should not be accepted uncritically.

They envisaged an initial Scandinavian ice advance in the North Sea basin to what is now The Wash. Eastward expansion of the southward flowing Lowestoft ice stream down eastern England was therefore confined by the southerly limit of the Scandinavian ice. As the Scandinavian ice retreated the axis of the Lowestoft ice stream shifted eastward into the North Sea basin, from where it spread radially westwards, southwards and eastwards (Fish and Whiteman, 2001, figure 8). In addition, Langford (1999, 2004a) provided unequivocal evidence that low-lying areas existed in the area of the present-day East Anglian Fens before the first (Anglian) major influx of Cretaceous material into the study area. At Stanground a sequence of deltaic to deepwater deposits infill a channel with its base at –5 m OD; overlying this sequence is a subaqueous slide deposit that represents the first influx of Cretaceous material at this site (Langford, 1999). At March a sequence of deltaic to deepwater deposits infill a channel with its base at more than –23 m OD; this sequence contains up to 15% Cretaceous material, but the first major influx of Cretaceous material is represented by the overlying subaqueous cohesionless flow (grain-flow) deposit (Langford, 1999). Furthermore, West (2007) and Gibbard *et al.* (2009) have identified deposits associated with a later (MIS 6) ice advance on the eastern side of the East Anglian Fens, and it is feasible, therefore, that diamictons related to that event have been ascribed to Lowestoft Till.

The results of this study and those of Corbett (1996, 2001a, b, 2002) and Andrews *et al.* (2002) have demonstrated the discriminatory potential of using sediment magnetic properties in the study of Anglian/Elsterian terrestrial glacigenic sequences in East Anglia. In combination (and possibly without further statistical analyses) the magnetic variables 10 mT, A1000 mT, MAGDIFF and MDF have the potential to discriminate between component facies of Middle Pleistocene chalk-rich diamictons, and related deposits, of lowland England. Using a particular grain-size fraction, however, presents problems when comparing with data from other studies that have used 'whole rock' samples, or when assessing source materials for which only 'whole rock' data are available. Analyses of magnetic characteristics of a wider grain size range, particularly finer grained material, therefore may provide further lines of evidence to investigate. For example, Walden *et al.* (1995) used a range of grain-size fractions (1 mm to $< 4\,\mu$m) as well as bulk samples to discriminate between different tills.

ACKNOWLEDGEMENTS

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REFERENCES

ALLEN, P., CHESHIRE, D.A. & WHITEMAN, C.A. 1991. The tills of southern East Anglia. In: Ehlers, J., Gibbard, P.L., Rose, J. (eds), *Glacial Deposits in Great Britain and Ireland*. Balkema, Rotterdam, 255–278.

ANDREWS, J.E., CORBETT, W.M., FUNNELL, B.M. & BOOTH, S.J. 2002. Pilot study in differentiating North Norfolk glacial sediments using mineral magnetic data. *Bulletin of the Geological Society of Norfolk*, **52**, 73–87.

BOWEN, D. Q. (ed.) 1999. *A Revised Correlation of Quaternary Deposits in the British Isles*. Geological Society Publishing House, Bath.

CLARK, C.D., EVANS, D.J.A., KHATWA, A., BRADWELL, T., JORDAN, C.J., MARSH, S.H., MITCHELL, W.A., BATEMAN, M.D. 2004. Map and GIS database of glacial landforms and features related to the last British Ice Sheet. *Boreas*, **33**, 359–375.

CLAYTON, K.M. 2000. Glacial erosion of the Wash and Fen basin and the deposition of the chalky till of eastern England. *Quaternary Science Reviews*, **19**, 811–822.

CORBETT, W.M. 1996. *Till Facies and Glaciation in parts of East Anglia*. PhD thesis, University of East Anglia, Norwich, 2 vols.

CORBETT, W.M. 2001a. A statistical re-examination of lithology and facies variation in the Chalky Boulderclay of Norfolk and Suffolk. *Bulletin of the Geological Society of Norfolk*, **51**, 5–53.

CORBETT, W.M. 2001b. Stratigraphy of the East Anglian Chalky Boulderclay Plateau based on statistical defferentiation of till facies. *Bulletin of the Geological Society of Norfolk*, **51**, 55–73.

CORBETT, W.M. 2002. Origin of Chalky Boulderclay (Lowestoft Till) in Norfolk and Suffolk based on mineral magnetic and facies variation. *Bulletin of the Geological Society of Norfolk*, **52**, 5–71.

DAVEY, N.D.W. 1991. A review of the Pleistocene geology of the Peterborough district. In: Lewis, S. G., Whiteman, C. A. & Bridgland, D. R. (eds), *Central East Anglia and the Fen Basin, Field Guide*. Quaternary Research Association, London, 150–162.

EHLERS, J. & GIBBARD, P.L. 1991. Anglian glacial deposits in Britain and the adjoining offshore region. In: Ehlers, J., Gibbard, P. L. & Rose, J. (eds), *Glacial Deposits in Great Britain and Ireland*. Balkema, Rotterdam, 17–24.

EHLERS, J., GIBBARD, P.L. & WHITEMAN, C.A. 1991. The glacial deposits of northwestern Norfolk. In: Ehlers, J., Gibbard, P. L. & Rose, J. (eds), *Glacial Deposits in Great Britain and Ireland*. Balkema, Rotterdam, 223–232.

FISH, P.R. & WHITEMAN, C.A. 2001. Chalk micropalaeontology and the provenance of Middle Pleistocene Lowestoft Formation till in eastern England. *Earth Surface Processes and Landforms*, **26**, 953–970.

GIBBARD, P.L., PASANEN, A.H, WEST, R.G., LUNKKA, J.P., BOREHAM, S, COHEN, K.M. & ROLFE, C. 2009. Late Middle Pleistocene glaciation in East Anglia, England. *Boreas*, **38**(3), 504–528.

HAMBLIN, R., MOORLOCK, B. & ROSE, J. 2000. A new glacial stratigraphy for eastern England. *Quaternary Newsletter*, **92**, 35–43.

HAMBLIN, R.J.O., MOORLOCK, B.S.P., ROSE, J., LEE, J.R., RIDING, J.B., BOOTH, S.J. AND PAWLEY, S.M. 2005. Revised pre-Devensian glacial stratigraphy in Norfolk, England, based on mapping and till provenance. *Netherlands Journal of Geosciences*, **84**, 77–85.

HORTON, A. 1989. Geology of the Peterborough district. *Memoir of the British Geological Survey*, Sheet 158, England and Wales. Her Majesty's Stationery Office, London, 44 pp.

KJÆR, K.H. 1999. Mode of subglacial transport deduced from till properties, Mýrdalsjökull, Iceland. *Sedimentary Geology*, **128**, 271–292.

LANGFORD, H.E. 1999. *Sedimentological, Palaeogeographical and Stratigraphical aspects of the Middle Pleistocene Geology of the Peterborough Area, Eastern England*. Unpublished PhD thesis, Anglia Polytechnic University, Cambridge (2 Vols).

LANGFORD, H.E. 2004a. Middle Pleistocene deposits at Stanground (Peterborough) and March, eastern England: a discussion based on new evidence. *Proceedings of the Geologists' Association*, **115**, 91–95.

LANGFORD, H.E. 2004b. Comments on the Anglian glaciation of the Fen Basin. In: Langford, H.E. & Briant, R.M. (eds), *Nene Valley*. Field Guide, Quaternary Research Association, Cambridge, 14–21.

LANGFORD, H.E. & BOREHAM, S. 1998. Buried channel deposits at March, Cambridgeshire, Eastern England. *Quaternary Newsletter*, **86**, 8–16.

MADDY, D. 1999. English Midlands. In: Bowen, D. Q. (ed.), *A Revised Correlation of Quaternary Deposits in the British Isles*. Geological Society Special Report No. 23, Geological Society Publishing House, Bath.

MAHER, B.A & HALLAM, D.F. 2005. Magnetic carriers and remanence mechanisms in magnetite-poor sediments of Pleistocene age, southern North Sea Basin. *Journal of Quaternary Science*, **20**(1), 79–94.

MITCHELL, G.F., PENNY, L.F., SHOTTON, F.W. & WEST, R.G. 1973. *A Correlation of Quaternary Deposits in the British Isles*. Geological Society Special Report 4. Geological Society, London.

PERRIN, R.M.S., DAVIES, H. & FISH, M.D. 1973. Lithology of the Chalk Boulderclay. *Nature Physical Science*, **245**, 101–104.

PERRIN, R.M.S., ROSE, J. & DAVIES, H. 1979. The distribution, variation and origin of pre-Devensian tills in eastern England. *Philosophical Transactions of the Royal Society of London, Series B*, **287**, 535–570.

ROSE, J. 1994. Major river systems of central and southern Britain during the Early and Middle Pleistocene. *Terra Nova*, **6**, 435–443.

ROSE, J. 2009. Early and Middle Pleistocene landscapes of eastern England. *Proceedings of the Geologists' Association*, **120**, 3–33.

WALDEN, J., SMITH, J.P. & DACKOMBE, R.V. 1987. The use of mineral magnetic analyses in the study of glacial diamicts: pilot study. *Journal of Quaternary Science*, **2**(1), 73–80.

WALDEN, J., SMITH, J.P. & DACKOMBE, R.V. 1992. Mineral magnetic analyses as a means of lithostratigraphic correlation and provenance of glacial diamicts: intra- and inter-unit variation. *Journal of Quaternary Science*, **7**(3), 187–272.

WALDEN, J., SMITH, J.P., DACKOMBE, R.V. & ROSE, J. 1995. Mineral magnetic analyses of glacial diamicts from the Midland Valley of Scotland. *Scottish Journal of Geology*, **31**, 79–89.

WEST, R.G. 2007. The Little Ouse River, the Waveney River and The Breckland: a joint history. *Transactions of the Suffolk Naturalist Society*, **43**, 35–39.

WHITEMAN, C. & LEWIS, S. 2000. Introduction to the Easter 2000 Field Meeting. In: Lewis, S. G., Whiteman, C. A. & Preece, R. C. (eds), *The Quaternary of Norfolk and Suffolk: Field Guide*. Quaternary Research Association, London, vii–xi.

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APPENDIX

For completeness the lithological variable data provided by W. M. Corbett for the study area are provided here (Table A1), and a comparison with Lowestoft Till samples from Norfolk and Suffolk using selected variables found to be important by Corbett (1996, 2001a) is presented as bivariate plots in Figure A1. Only in the $> 63\,\mu$m and $> 63 < 250\,\mu$m non-carbonate fractions (Figs A1b and e) is there any commonality between the Lowestoft Till samples from the study area and the Lowestoft Till of Corbett (2001a). For all other variables there is a wide spread of data for Lowestoft Till samples from the study area. For example, for the $< 63\,\mu$m non-carbonate and the $< 63\,\mu$m carbonate fractions the data for Lowestoft Till samples range from $< 5\%$ to $> 60\%$, compared with respective ranges of about 30–40% and 35–45% for the Chalky Boulderclay facies (s 1a). There is also a wide spread of data for the $> 63\,\mu$m non-carbonate fraction in the substrate samples (Fig. A1b) that is not apparent in the Lowestoft Till samples of the study area.

Table A1. Lithological data from the study area (Data provided by W.M. Corbett)

Location	Sample	Percentage total grain-size fraction (μm)				Total	Percentage carbonate grain-size fraction (μm)				Percentage non-carbonate grain-size fraction (μm)			
	number	> 500	500–250	250–63	< 63	carbonate	> 500	500–250	250–63	< 63	> 500	500–250	250–63	< 63
March	NCRSa	0.2	1.1	63.5	35.2	15.3	0.1	0.3	9.3	5.6	0.1	0.8	54.2	29.6
	NCRSb	4.4	2.1	6.8	86.7	11.0	1.8	0.8	2.8	5.6	2.6	1.3	4.0	81.1
	CRD3a	7.41	2.45	8	82.13	43.1	5.35	0.74	2.09	34.92	2.07	1.71	5.91	47.21
	CRD3b	9.63	2.22	8.3	79.85	46.4	7.9	0.63	2.34	35.54	1.73	1.59	5.97	44.31
Stanground	NCRS1a	19.4	11.0	17.4	52.2	20.6	6.3	4.1	7.0	3.2	13.1	6.9	10.4	49.0
	NCRS1b	21.9	12.2	16.9	46.0	25.0	9.1	4.9	7.6	3.4	15.8	7.3	9.3	42.6
	NCRS2	3.32	2.37	9.73	84.58	25.1	1.15	0.61	2.59	20.75	2.17	1.77	7.14	63.82
	CRD4a	5.4	3.84	12.15	78.6	33.9	2.86	0.6	2.23	28.21	2.54	3.24	9.92	50.39
	CRD4b	10.13	3.42	11.73	74.73	77.8	5.81	0.7	2.03	69.26	4.32	2.72	9.69	5.47
Alconbury	CRD4c	13.88	3.00	7.48	75.64	62.5	11.06	1.11	3.13	47.2	2.82	1.89	4.35	28.43
	CRD4d	10.69	3.03	8.25	78.03	59.4	7.84	1.08	2.82	47.66	2.85	1.95	5.43	30.37
Chesterton	CRD1	7.4	2.93	11.47	78.21	24.3	3.45	0.98	2.39	17.48	3.94	1.95	9.08	60.72
Hill	CRD2	9.07	4.22	11.10	75.61	57.2	5.98	1.02	2.95	47.26	3.1	3.21	8.15	28.35
Ketton	CRD6a	13.3	2.2	7.7	76.8	42.1	10.7	0.9	1.9	28.0	2.7	1.4	5.8	48.0
	CRD6b	10.3	2.9	9.8	77.0	21.6	5.3	0.9	2.2	13.2	5.0	2.0	7.5	63.9
	CRD6c	16.3	3.1	9.2	71.4	15.9	9.6	0.8	2.3	3.2	6.7	2.3	6.9	68.2

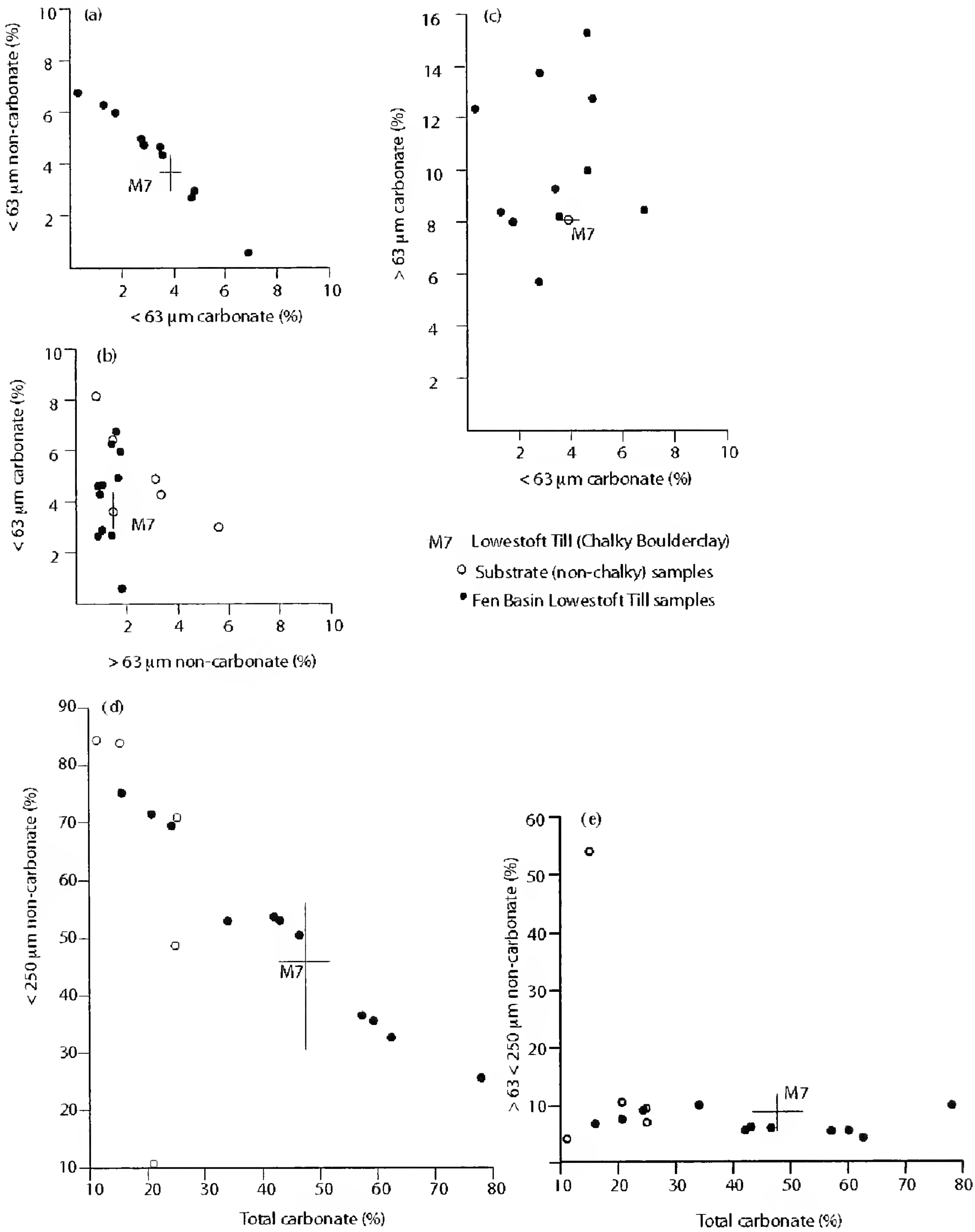

Fig. A1. Bivariate plots of the discriminatory lithological variable data. The 1σ standard deviation for the measured variable cluster M7 is shown where available. (Data for the study area were provided by W. M. Corbett. Data for the M7 cluster are from Corbett 2002)

A THRUST-STACKED ORIGIN FOR INTER-STRATIFIED TILL SEQUENCES: AN EXAMPLE FROM WEYBOURNE TOWN PIT, NORTH NORFOLK, UK.

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ABSTRACT

Subglacial processes, and their temporal and spatial variations, play a significant role in controlling the behaviour of ice masses. The processes leading to the formation and emplacement of inter-stratified sequences of subglacial tills are, however, particularly poorly understood. Such sequences are relatively widespread, having been found in, for example, the UK, Canada and Germany. Those of the Weybourne area of north Norfolk, UK, are especially interesting in that the majority of the sediment pile is composed of repeated, inter-laminated subglacial till units with very few non-till units present. Many contrasting mechanisms for this highly contorted sequence have been suggested throughout a long history of investigation at the site and even the direction of ice advance that produced the deformation has proved difficult to resolve. In order to address this, the current study combines lithological, structural and palynological techniques to investigate the exposure at Weybourne Town Pit. A re-interpretation of the sequence is presented in which the tills are seen to have been derived initially as subglacial tills from advances of the Middle Pleistocene British Ice Sheet flowing southwards along the east coast of England. A stage of brittle deformation linked to oscillation of the ice margin is identified as occurring after the primary deposition phase. This secondary deformation phase was responsible for localised thrust-stacking of the till blocks and resulted in the inter-stratified sequence seen today.

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INTRODUCTION

Investigation of the dynamics of the major Quaternary ice sheets that existed across northern Europe and North America has revealed a highly significant role for subglacial processes, and their temporal and spatial variations, in controlling the behaviour of ice masses (Evans *et al.*, 2006). These findings are important in the context of the likely response of modern ice sheets, especially the Greenland and western Antarctic ice sheets, to perturbation by current and future climate changes (Hughes, 1996; Bentley, 1997).

Sequences composed of inter-stratified subglacial tills are widespread, having been identified in, for example, the UK, Canada and Germany (Fish et al., 2000; Friele and Clague, 2002; Menzies and Ellwanger, 2011). The sequences are composed of stacked, repeated units of two or more till lithofacies most often inter-digitated with units of non-till lithofacies. These units may cross-cut each other, truncating the internal structure of the unit. Exposures range in height between 2 m and 11 m. However, the formation of these sequences is particularly poorly understood and several contrasting mechanisms have been proposed, including: (1) the confluence of ice sheets (Banham and Ranson, 1956; Cox and Nickless, 1972; Ehlers and Gibbard, 1991; Lunkka, 1994), (2) different advances or multiple lobes of the same ice sheet (Straw, 1965; Perrin *et al.*, 1979; Ehlers *et al.*, 1987, 1991; Hamblin *et al.*, 2005), (3) a sedimentary 'melt-out' origin (Haldorsen and Shaw, 1982; Shaw 1982, 1983) and (4) glaciotectonic processes associated with a subglacial deforming bed (Hart et al., 1990; van der Meer *et al.*, 2003; Menzies *et al.*, 2006).

The Weybourne area of north Norfolk, UK is one region where such inter-stratified tills are exposed. The north Norfolk area, itself, is seen to possess one of the best Early and Middle Pleistocene sedimentary records in north-western Europe (Lee *et al.*, 2008; Rose, 2008) and inter-stratified tills are readily visible in a highly contorted sequence at Weybourne Town Pit (National Grid Reference TG 114 430). The sequence here is especially interesting in that the majority of the sediment pile is composed of tills inter-stratified with one another. Very few non-till lithofacies are present. This area has been affected by a number of Early and Middle Pleistocene glaciations (Hamblin *et al.*, 2005) and the sediments at the pit are believed to relate to the latter of these glaciations which reached its most southerly limit just to the south of the pit, along the line of the Cromer Ridge.

Despite a long history of investigation, the mechanisms for the emplacement of the inter-stratified facies at Weybourne Town Pit remain enigmatic (Fish *et al.*, 2000; Pawley *et al.*, 2004; Hart, 2007). Understanding of the direction of ice movement responsible for the inter-stratified tills is also poor, with contrasting interpretations of structural and lithological evidence suggesting numerous different directions (Table 1). For example, structural analysis presented in Fish *et al.* (2000), indicates that ice flow from the southwest was responsible for the chalky and sandy tills exposed in the pit, whilst lithological evidence implies an easterly provenance. Till fabrics examined in Hart (2007), however, imply ice flow directions from the northeast and northwest.

In order to address the controversy surrounding the formation of the inter-stratified sequence and the direction of ice movement responsible for the tills, this paper presents an investigation of the Middle Pleistocene sequence at Weybourne Town Pit, north Norfolk, UK. A suite of structural, lithological and palynological techniques are combined to thoroughly examine the exposure. The inter-stratified sequence is interpreted as comprising a primary stage of till deposition and a

Table 1. Direction of ice advances responsible for the tills of the north Norfolk area, as suggested by some earlier researchers. Study locations: NN= north Norfolk, C= Weybourne Coast and WTP= Weybourne Town Pit. Ice direction: SW-W= ice from between the southwest and south, E&W= ice from the east and west. Lithology: ST=sandy till and CT=chalky till.

Reference	Study Location	Methodology	Direction	
Banham and Ranson (1965)	C & WTP	Clast fabric	NE & NNE	
		Fold orientation	SSW-SW	
Ehlers *et al.* (1987)	NN	Stratigraphy	SW	
		Clast fabric	SW & N	
		Thrust orientation	W & SW	
Fish *et al.* (2000)	C & WTP		ST	CT
		Stratigraphy	W-NW-N	W & NW
		Clast fabric	NNW & SSE	NNW, NE & N
		Fold orientation	SW	SW
		Chalk micropalaeontology	E & W	E & W
Fish and Whiteman (2001)	NN & WTP		ST	CT
		Chalk micropalaeontology	NW	NNW
Pawley *et al.* (2004)	C		ST	CT
		Clast fabric	NNW	N/A
		Fold orientations	NNW	N/A
		Chalk micropalaeontology	N/A	N
Hart (2007)	WTP		ST	CT
		Clast fabric	NE	NW
		Fold orientation	NNW	NNW

secondary phase of deformation through till remobilisation and emplacement. Flow directions for the ice responsible for depositing the tills are determined, a model for ice-marginal thrust-stacking of till blocks is outlined and the stratigraphic implications of this are discussed.

STUDY SITE AND GEOLOGICAL CONTEXT

Weybourne Town Pit (National Grid Reference TG 114 430), a disused brick pit located to the east of the village of Weybourne in north Norfolk, forms the locality for this study. The pit is approximately 50 m by 20 m in area and 4 m deep. A south-facing exposure of approximately 5 m length and 2 m height reveals a contorted series of Quaternary sediments on the western side of the north quarry wall. The pit lies just to the south of the Late Pleistocene (Devensian) ice limit (Pawley *et al.*, 2006) within an area of gently undulating topography (Figure 1). To the south of the pit, the ground rises towards the Cromer Ridge- a major Middle Pleistocene ice marginal push moraine and outwash complex (Hart, 1990; Pawley *et al.*, 2005). To the north, the ground slopes gently to the modern coastline, where low cliffs (1-10m) are present.

A number of different lithostratigraphical schemes have been proposed for the area's glacial deposits (Table 2) and the exact number of glaciations the sequences record is contentious. As early as 1877 Geikie suggested that the region had been affected by four glaciations, although this model was largely refuted at the time (Geikie, 1877 in Baden-Powell, 1948). Later, Baden-Powell (1948) advocated the existence of four tills. Following this, two major lithofacies associations were invoked (Banham & Ranson, 1956) and ascribed to a single ice sheet expansion during the Middle Pleistocene (Perrin *et al.*, 1979; Bowen *et al.*, 1986). Lunkka (1994) expanded the scheme to involve five tills and these became attributed to three separate ice sheet expansions occurring throughout the Pleistocene (Hamblin *et al.*, 2000).

However, the published stratigraphies still failed to resolve observed differences in the succession between north Norfolk and the Waveney Valley area to the west. As a result, a reappraisal of the region's stratigraphy was undertaken by Lee *et al.* (2004) and Hamblin *et al.* (2005). They proposed a more robust scheme involving four formations. The stratigraphical nomenclature detailed in Lee *et al.* (2004) and outlined in Hamblin *et al.* (2005) is adopted in this study (Table 3).

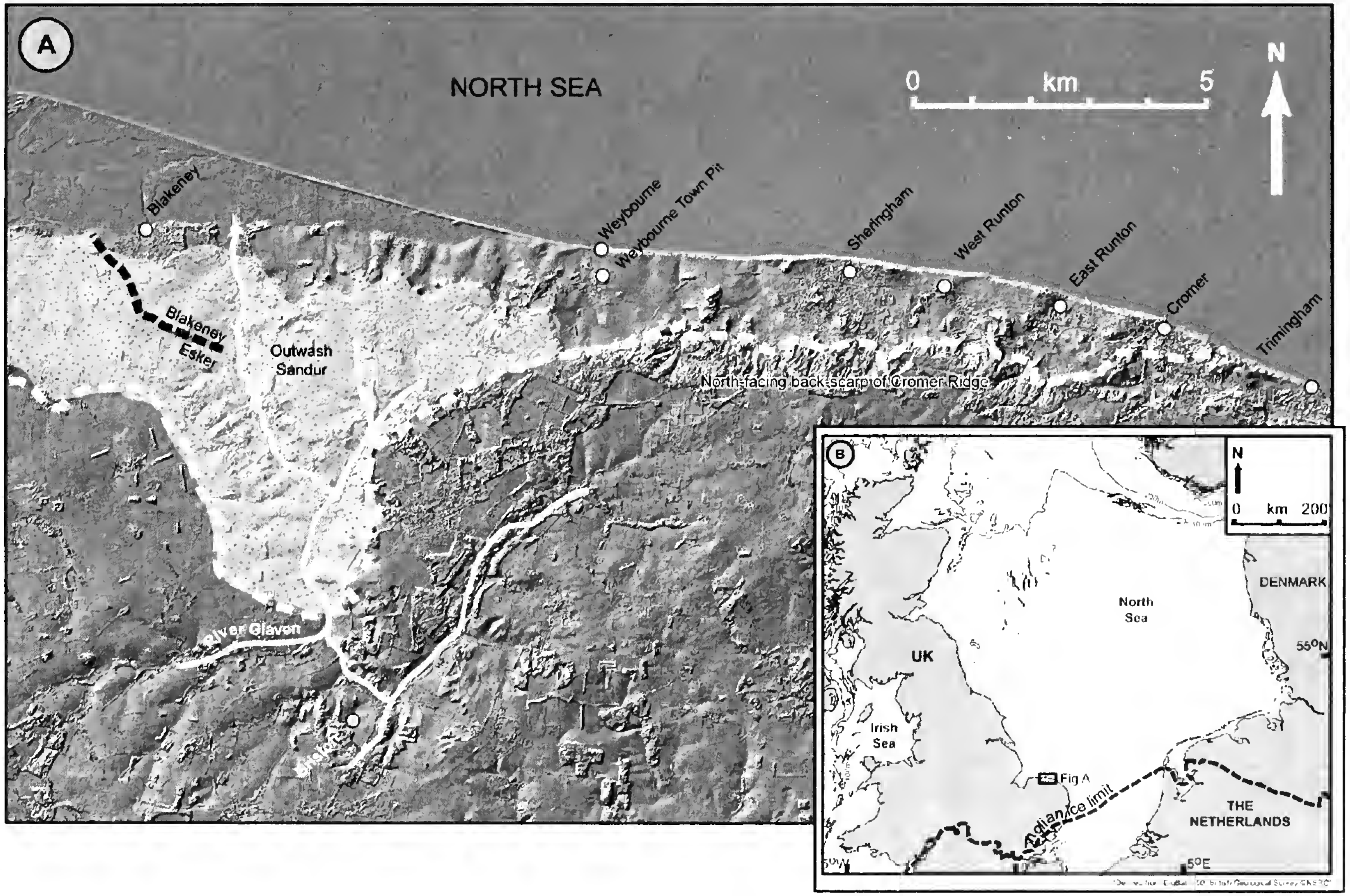

Figure 1. The Weybourne area of Norfolk, UK and location of the Weybourne Town Pit study site. Major glacial geomorphological features (A) and regional context (B) are shown. Middle Pleistocene (Anglian) ice limit after Bowen *et al.* (1986).

Table 2. Previous lithostratigraphical schemes for the glacial deposits of Norfolk.

<table>
<tr><th>Baden-Powell (1948)</th><th>Banham & Ranson (1956)</th><th>Lunkka (1994)</th><th>Lee et al. (2004), Hamblin et al. (2005)</th></tr>
<tr><td></td><td>Briton's Lane Sand and Gravel</td><td></td><td>Briton's Lane Formation</td></tr>
<tr><td>Hunstanton Boulder Clay</td><td rowspan="2">Lowestoft Till</td><td rowspan="2">Lowestoft Till Formation
Marly Drift Member</td><td>Sheringham Cliffs Formation</td></tr>
<tr><td>Gipping Boulder Clay
Lowestoft Boulder Clay</td><td rowspan="3">Lowestoft Formation</td></tr>
<tr><td rowspan="3">Cromer Till</td><td>Third Cromer Till</td><td>Cromer Diamicton Member
Mundesley Diamicton Member</td></tr>
<tr><td>Second Cromer Till</td><td>Walcott Diamicton Member</td></tr>
<tr><td>First Cromer Till</td><td>Happisburgh Diamicton Member</td><td>Happisburgh Formation</td></tr>
</table>

Table 3. The pre-Devensian glacial stratigraphy of Norfolk, after Lee *et al.* (2004) and Hamblin *et al.* (2005).

Formation	Members	Characteristics
Briton's Lane Formation	Briton's Lane Sand and Gravel Member	Sands and gravels
Sheringham Cliffs Formation	Weybourne Town Till Member	Silt and chalk-rich matrix-supported diamicton
	Runton Till Member	Dark grey (10YR 4/1) to very dark greyish brown (2.5YR 3/2) matrix-supported diamicton.
	Bacton Green Till Member	Dark yellowish sandy brown (10YR 4/4) to dark grey (5Y 5/1) matrix-supported diamicton with sand beds.
Lowestoft Formation	Walcott Till Member	Olive-grey (2.5Y 5/1) to olive-brown (2.5Y 4/3) silt-rich, weakly-stratified matrix-supported diamicton.
	Lowestoft Till Member	Clay-rich, massive matrix-supported diamicton.
Happisburgh Formation	Corton Till Member	Light olive-brown (2.5Y 5/4) to olive-brown (2.5Y 4/4), sandy, generally massive matrix-supported diamicton.
	Happisburgh Till Member	Yellowish grey (2.5Y 4/1) to grey (5Y 4/1), generally massive matrix-supported diamicton.

METHODOLOGY

Weybourne Town Pit was visited between 2002 and 2003 (Lee, 2003) with follow up work by the present authors in 2008. Macro-scale features were described from the exposure on the western side of the north quarry wall. Sediment type, type of bedding, unit geometry and structure were recorded and bulk samples of the diamicton units were collected. These samples were separated into 4-8 mm and 8-16 mm fractions through sieving and the lithology of clasts retained from these fractions was examined in order to determine till provenance. Till provenance was further refined by sampling the diamicton units for palynological analysis. Two samples were taken from each of the diamicton lithofacies identified. These samples were processed following the procedures outlined in Wood *et al.* (1996) and prepared using the sodium hexametaphosphate method of Riding and Kyffin-Hughes (2004; 2006). Palynomorphs were counted and categorised according to age, stratigraphical range and geographical distribution.

DESCRIPTION

Lithofacies

Eleven units, divisible into 4 lithofacies have been identified by the current study at Weybourne Town Pit (Figure 2):

Lithofacies A (Unit 1): Lithofacies A consists of a pale yellow (2.5Y 7/3) to light yellowish brown (2.5Y 6/3), faintly laminated, highly calcareous marl. Within the exposure this lithofacies is restricted to a single unit, Unit 1, which has a maximum observed thickness of 0.58 m.

Lithofacies B (Unit 2): Lithofacies B comprises an olive yellow (2.5Y 7/6) to brownish yellow (10YR 6/8) silty sand which is weakly stratified and exhibits convolute bedding and flame-like contortions. This lithofacies can be traced discontinuously throughout the entire length of the section and is restricted to a single unit, Unit 2, which ranges in observed thickness between 0.15-0.25 m.

Lithofacies C (Units 3, 5, 8 and 10): Lithofacies C consists of a light yellowish brown (2.5Y 6/4) to brownish yellow (10YR 6/6), matrix-supported diamicton with a clayey sand matrix and moderate calcium carbonate content (17-19%). Localised contorted

sandy inclusions and discontinuous laminae of more calcareous material are present. This lithofacies occurs as several individual units in the upper 1.5m of the section which range in thickness between 0.1-0.26m. These are the darker horizons seen in the top half of Figure 2.

Lithofacies D (Units 4, 6, 7, 9 and 11): Lithofacies D comprises a light grey (5Y 7/2) to pale yellow (2.5Y 7/4), matrix-supported diamicton, exhibiting a highly calcareous (61-73%) clayey silt matrix. Localised contorted inclusions of sandy material are present. This lithofacies also occurs as several individual units in the upper 1.5 m of the section: the lighter horizons seen in the top half of Figure 2. These range in thickness between 0.1-1.6 m.

Structure

Twelve bounding structures between individual units are identified in the current study. These are typically sharp, 2-3 mm thick and dip at shallow angles towards a general northerly direction. Repetition of units of Lithofacies C and D is evident in the upper 1.5 m of the section. The lower portion of the section, meanwhile, is composed of a single unit of Lithofacies B overlying one unit of Lithofacies A. The bounding structures and geometry of the individual units are described below (Figures 2 & 3):

Structure 1 (Unit 1-2 discontinuity): Structure 1 represents a sharp, sub-horizontal, slightly undulatory boundary separating Units 1 and 2.

Structure 2 (Unit 2-3 discontinuity): Structure 2 is undulatory, rises from east to west by approximately 0.4m and is generally sharp in appearance.

Structure 3: Structure 3 comprises a series of small-scale extensional faults which offsets Structure 2.

Structure 4 (Unit 3-4 discontinuity): Structure 4 is sharp and irregular and dips at shallow angles towards the northwest-northeast.

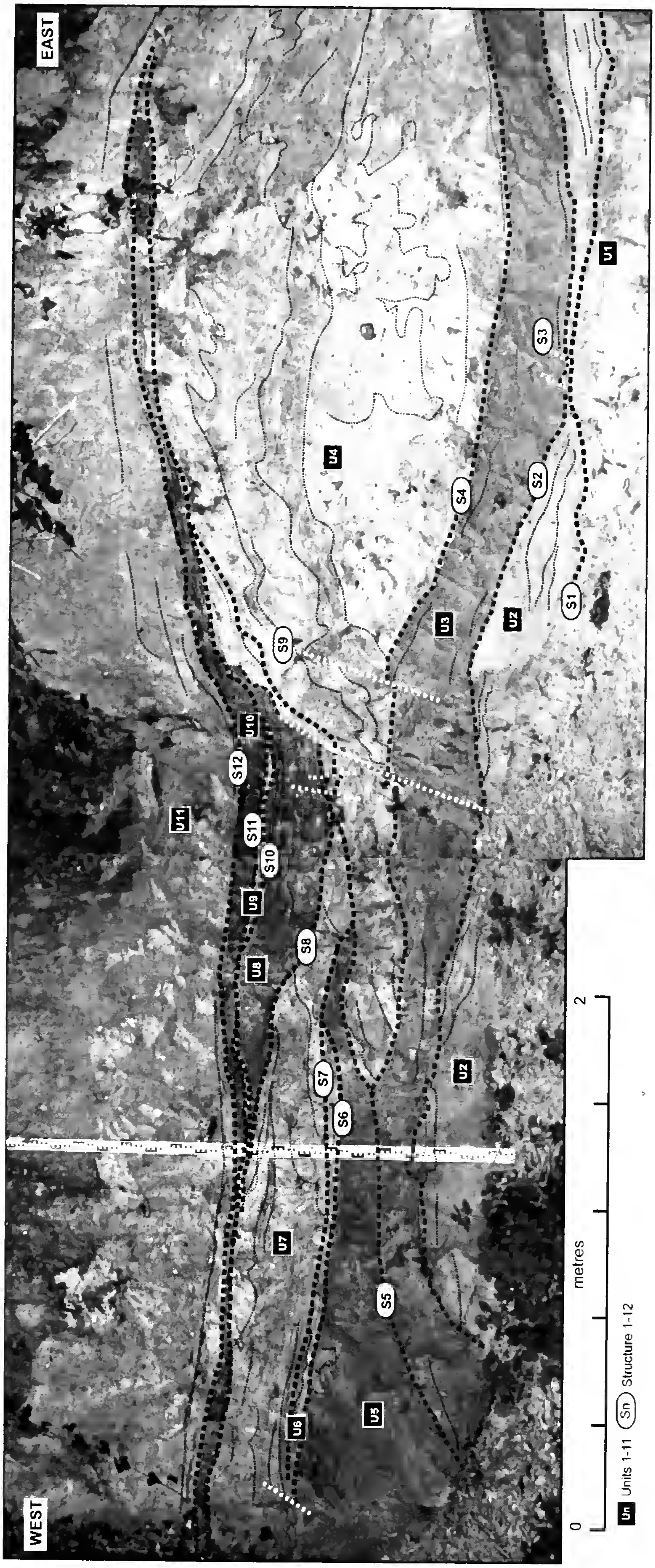

Figure 2. Lithological and structural interpretation of the north quarry wall exposure at Weybourne Town Pit. Repetition of Lithofacies C (Units 3, 5, 8 and 10)) and Lithofacies D (Units 4, 5, 6, 7, 9 and 11) can be seen in the upper 1.5 m of the section, overlying a single unit of Lithofacies B (Unit 2) and a basal unit comprised of Lithofacies A (Unit 1).

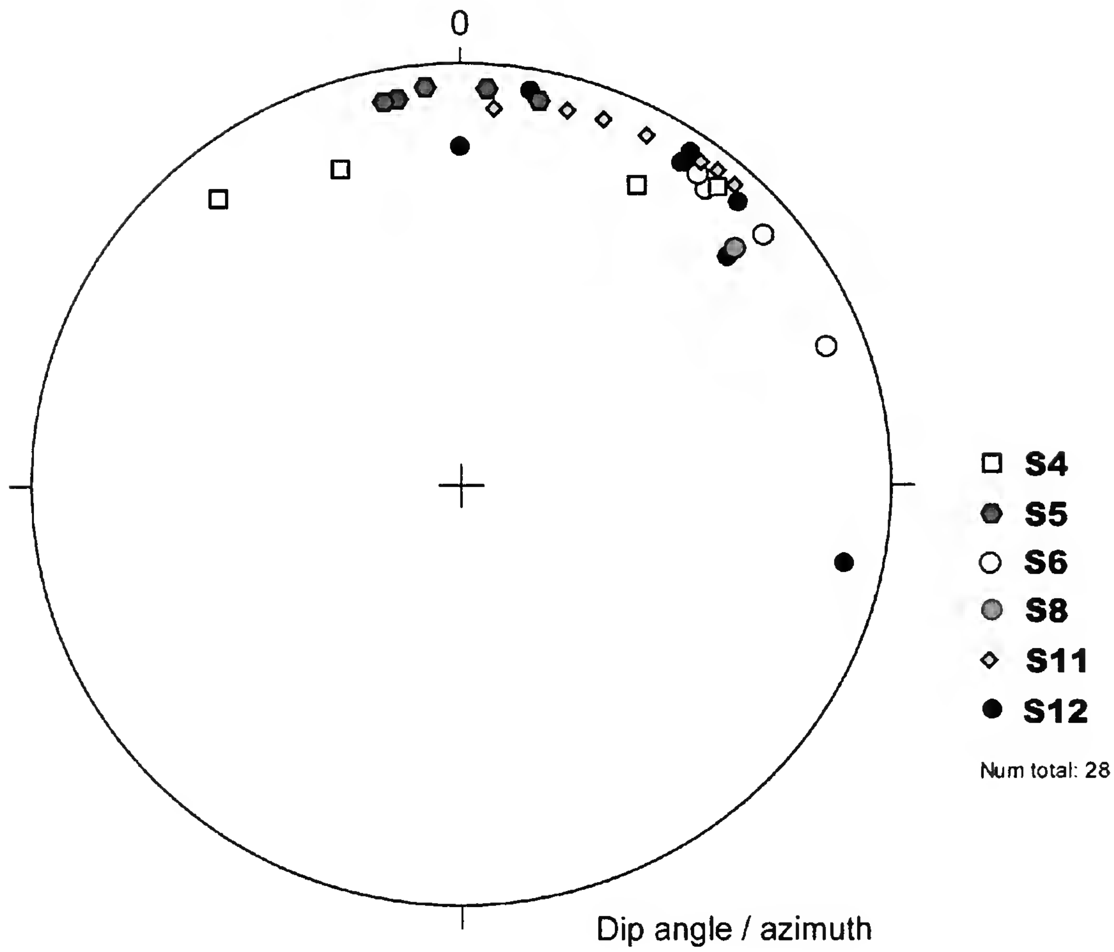

Figure 3. Equal area stereographic projection for planar structures identified within Weybourne Town Pit. Bounding structures, prefix S, as marked on Figure 2 and in the text. A general dip at shallow angels between the northwest and northeast can be seen.

Structure 5 (Unit 4-5 and 3-5 discontinuity): Unit 3 and 4 and Structure 4 are truncated by Structure 5 towards the western half of the section.

Structure 6 (Unit 5-6 discontinuity): Structure 6 dips at a shallow angle to the northeast and east-northeast.

Structure 7 (Unit 6-7, 5-7 and 4-7 discontinuity): Structure 7 is an undulating and sharp discontinuity that can be traced throughout the western and central parts of the section. This feature cross-cuts Units 4, 5 and 6 and Structures 5 and 6.

Structure 8 (Unit 7-8 discontinuity): Structure 8 dips towards the northeast and is generally sharp. In very localised areas the structure has a flame-like appearance.

Structure 9: Structure 9 comprises a series of high-angle extensional faults with a down throw to the west which cross-cuts Unit 4 and impinge upon Units 2, 3, 7 and 8 and structures 2, 4, 7 and 8.

Structure 10 (Unit 8-10 discontinuity): Structure 10 is sharp and slightly irregular and truncates the extensional faults of Structure 9.

Structure 11 (Unit 4-10, 7-10, 8-10 and 9-10 discontinuity): Structure 11 can be traced along the entire length of the section where it truncates Units 4, 7, 8 and 9 and Structures 7, 8 and 10. It is sharp with localised diffuse areas and dips towards the northeast at shallow angles.

Structure 12 (Unit 10-11 discontinuity): Structure 12 forms an undulating discontinuity extending across the whole length of the section, dipping towards the north and northeast at shallow angles.

Clast lithology

The clast population of Lithofacies C is dominated by lithologies derived from older Pleistocene deposits (93.0-93.6%), including: white, brown and chatter-marked flint, quartzite and shell and wood fragments (Table 4). A smaller Cretaceous component, including black flint (4.4-5.9%) and sparse chalk pebbles (0.2-0.6%), is also present. Jurassic ironstone was represented in the 4-8 mm fraction and crystalline clasts included quartz- and micaceous schists. In contrast, the clast composition of Lithofacies D is dominated by Cretaceous lithologies including chalk (59.9-79.5%) and black flint (4.1-6.5%) (Table 4). Clasts derived from Pleistocene deposits occur to a lesser extent and include white, brown and chatter-marked flint (12.6-28.3%) and quartzite (2.0-4.0%). Minor Jurassic (oolitic limestone 0.1%) and Permo-Triass (red sandstone 0.6%) components were also noted.

Table 4. Clast lithological composition of Lithofacies C and D.

Lithofacies	**C**		**D**	
Unit	3,5 and 8		4 and 11	
Fraction (mm)	4-8	8-16	4-8	8-16
Number of clasts	862	158	1009	202
Sedimentary lithologies				
Pleistocene (%)				
Total	93.0	93.6	15.3	33.3
Chatter-marked, white/ brown flint	70.4	86.7	12.6	28.3
Vein quartz, quartzite, schorl	10.4	5.0	2.0	4.0
Rhaxella and greensand chert	0.8	0.6	0.1	1.0
Shell, wood	11.4	1.3	0.6	0.0
Cretaceous (%)				
Total	6.2	5.0	83.6	65.8
Chalk	0.2	0.6	79.5	59.9
Black flint	5.9	4.4	4.1	6.5
Carstone, glauconitic sandstone	0.1	0.0	0.0	0.0
Jurassic (%)				
Total	0.0	1.3	0.1	0.1
Sandstone, limestone, ironstone, shell	0.0	1.3	0.0	0.1
Oolitic sandstone, limestone, chert	0.0	0.0	0.1	0.0
Permo-Triassic (%)				
Total	0.0	0.0	0.6	0.0
Red sandstone, evaporate	0.0	0.0	0.6	0.0
Crystalline lithologies				
Scotland (%)				
Total	0.6	0.0	0.4	0.0
Dalradian, gabbro	0.6	0.0	0.1	0.0
Granite, granodiorite, quartzporphyry	0.0	0.0	0.1	0.0
Acid porphyry	0.0	0.0	0.2	0.0
Scotland/ northern England (%)				
Total	0.1	0.0	0.0	0.0
Quartz dolerite / basalt	0.1	0.0	0.0	0.0
Unknown lithology (%)	0.1	0.0	0.2	0.0

Table 5. The sampled palynomorph content of Lithofacies C and D.

Lithofacies	C		D	
Unit	3	8	4	11
Grains per slide	716	295	1155	1210
Quaternary forms (%)	1.7	9.8	7.8	12.6
Palaeogene (%)				
Dinoflagellate cysts	0.4	1.0	2.9	10.6
Cretaceous (%)				
miospores	1.8	0.3	1.4	0.9
Dinoflagellate cysts	1.2	1.4	3.2	4.5
Jurassic (%)				
miospores	12.8	17.9	14.5	26.7
microplankton	1.8	1.4	2.5	7.3
Carboniferous (%)				
miospores	29.9	2.7	3.8	4.0
Non-age diagnostic forms (%)	51.3	65.5	63.9	43.4

Palynology

Palynomorph assemblages from Lithofacies C (samples from Units 3 and 8 in Figure 2) are dominated by Carboniferous forms (Table 5). Westphalian (*Cirratriradites saturni*) and Viséan/Namurian (*Tripartites trilinguis*) markers are also present. Long-ranging Mid-Late Jurassic miospores are relatively common, including *Callialasporites* spp., *Classopollis* spp. and *Cyathidites* spp. Jurassic microplankton are relatively scarce but both *Halosphaeropsis liassica* derived from the Lower Toarcian (Bucefalo Palliani and Riding, 2003) and *Cribroperidinium globatum*, a key Kimmeridgian marker, are present. Cretaceous material is rare but includes the Lower Cretaceous spores *Appendicisporites* and *Cicatricosporites* and the Upper Cretaceous dinoflagellate cyst *Spongodinium delitiense*. A sparse Palaeogene input including *Cordosphaeridium gracile* and *Dracodinium*-the latter genus derived from the early-mid Miocene (Powell, 1992)-is also recognised. Somewhat variable levels of Quaternary pollen are present.

Samples from Lithofacies D (taken from units 4 and 11 in Figure 2) are significantly richer in organic palynomorphs than those from Lithofacies C (Table 5). The Carboniferous content is of low quantity and diversity, with only *Densosporites* spp. and *Lycosphora pusilla* recovered. Conversely, the number of Middle Jurassic miospores is relatively high and includes *Callialasporites* spp., *Classopollis* spp. and *Cyathidites* spp. Jurassic microplankton are also evident in higher percentages than in Lithofacies C, with Lower Toarcian (*Halosphaeropsis liassica* and *Nannoceratopsis gracilis*) markers identified. *Cribroperidinium globatum* and *Cribroperidinium longicorne*, which are strongly indicative of the Kimmeridgian (Riding and Thomas, 1992), were also found. Lower Cretaceous spores are rare but Cretaceous dinoflagellate cysts are present in significant proportions, with the Santonian-Campanian form *Senoniasphaera protrusa* and *Xenascus wetzelii* from the Campanian/Early Maastrichtian observed. No stratigraphically significant Palaeogene dinoflagellate cysts were observed.

INTERPRETATION

Palaeoenvironmental interpretation

Lithofacies A

The fine-grained texture and faint stratification of Lithofacies A suggest deposition within a very low energy subaqueous environment. Derivation from erosion of a local Chalk outcrop is implied by the highly calcareous nature of the lithofacies.

Lithofacies B

Lithofacies B posses a silty-sand texture which is indicative of deposition within a low to moderate energy subaqueous environment. Faint stratification implies minor changes in flow regime or sediment source. Synsedimentary flame structures and convolute-bedding provide evidence for dewatering and indicate rapid and high sedimentation rates, coupled with an elevated porewater content.

Lithofacies C

Lithofacies C occurs as several individual units exposed within the upper portion of the section. The brown coloration, clayey sand matrix, flint-dominated clast content and moderate calcium carbonate concentration of Lithofacies C mirror that of the Bacton Green Till Member of the Sheringham Cliffs Formation (Lee *et al*., 2004). Internal ductile deformation structures suggest deposition under conditions of high pore-water content, most likely as a subglacial till. Clast lithological analysis reveals that Lithofacies C is dominated by locally-sourced lithologies derived from the reworking of pre-existing Pleistocene outcrops. Further travelled clast lithologies include schists and quartz dolerite from northern Britain and ironstones hailing from the Lower Jurassic Redcar Mudstone and/or Cleveland Ironstone formations. Furthermore, palynomorph contents include Jurassic forms from the Yorkshire Basin and sparse Lower Cretaceous palynomorphs from East Yorkshire and/or Lincolnshire. As such, the ice originally responsible for the deposition of Lithofacies C is interpreted to have travelled from northern Britain.

Lithofacies D

The distinctive coloration, highly calcareous matrix and high chalk clast content indicate that the parent material of Lithofacies D is the Weybourne Town Till Member of the Sheringham Cliffs Formation (Lee *et al*., 2004). Evidence for internal

ductile deformation structures implies that this till was deposited under conditions of high pore-water content, most likely as a subglacial till. Clast lithological analysis provides evidence for Cretaceous clasts derived from the Santonian-Campanian and Campanian-Maastrichtian Chalk zones of Lincolnshire and the western margin of the North Sea Basin.

Allochthonous palynomorph contents also demonstrate derivation from northern Britain. Indeed, a Carboniferous component characteristic of that in Northumberland, Durham and the Midland Valley of Scotland is present. Such content precludes derivation of this till from the northeast, across the North Sea, as Carboniferous strata are absent at the surface within this area (Lee *et al.*, 2002; Riding *et al.*, 2003).

Structural relationships

Each of the unit contacts (Structure 1, 2, 4, 5, 6, 7, 8, 10, 11 and 12) identified in Figure 2 is sharp and irregular. They all truncate the internal fabric of the underlying unit and Structures 5, 7 and 11 each truncate a number of units. This suggests attenuation of these units prior to and/or during emplacement of the overlying unit and implies a stage of brittle deformation occurring after the initial deposition of Lithofacies A, B, C and D material.

The internal structure of units 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 is also orientated sub-obliquely to their respective underlying unit contact and so a tectonic rather than sedimentary mechanism for the emplacement of these units may be inferred. No meso-scale folds have been recognised within the sequence, indicating that the tectonic deformation leading to the juxtaposition of these units was predominantly brittle in nature. Consequently, the brittle deformation stage which truncated the upper portions of each of these units may have been contemporaneous with the tectonic emplacement of each of the overlying units.

Synsedimentary flame structures and convolute-bedding contained within the internal fabric of units of Lithofacies B, C and D material, provide evidence for ductile deformation. In light of the above interpretation, this ductile deformation must have occurred prior to the emplacement of these units in their current positions. The onset of brittle deformation is facilitated either by a sufficient time-period having elapsed between the initial ductile deformation of the units of Lithofacies B, C and D material and the subsequent brittle deformation stage for drying of the sediments or

by dewatering of the sediments during the subsequent brittle deformation stage itself. Brittle deformation resulting from freezing of the sediments is unlikely given the tendency towards pressure melting found in subglacial and ice-marginal environments.

The unit contacts are clearly cross-cutting with structurally higher discontinuities (for example S8, 10 and 11) in many cases truncating underlying structures (for example S5 and 7). These cross-cutting relationships imply that the relative age of emplacement of these units get generally younger upwards throughout the sequence. Whilst this is the simplest explanation, the entrainment of more than one thrusted unit during subsequent thrusting stages is not impossible and as such deviation from the relative younging upwards model may occur.

The similar geometry and orientation of these structures means that they probably formed during the same deformation event, rather then several discrete phases of deformation separated by large time-spans. Indeed, the repeated stacking of units of two lithofacies (Lithofacies C and D) implies the reworking of pre-existing material during one deformation event. The inter-stratified nature of the units is, therefore, consistent with a reworking phase of repeated thrust formation, shearing of pre-existing material along these thrusts and stacking of the resulting units which post-dates the initial formation of the Lithofacies B, C and D and given its lithostratigraphical position, Lithofacies A.

Dip angles and azimuth directions obtained from the contacts between the till units (Structures 2, 4, 5, 6, 7, 8, 10 and 11) reveal a dip at shallow angles towards the northwest, north and northeast. The sense of movement along these thrust shear planes is, therefore, towards the south, implying that the stress responsible for this brittle deformation was applied from a northerly direction.

The base of Unit 1 lies below that of the exposure and so little inference can be made as to the mechanism of emplacement for this unit. Nearby borehole logs reveal the occurrence of similar units at National Grid Reference TG 110 433, 115 431 and 110 430. The elevation of these units varies (units tops at +5.39 mOD, +14.6 mOD and +9.86 mOD, respectively), as does the unit thickness (8.84 m, 2.05 m and 12.2 m, respectively). It is not known whether these units are in situ or have been subjected to thrusting processes, as seen for Units 2-11 at the pit.

DISCUSSION

Lithostratigraphy and till provenance

The lithological, structural and palynological evidence presented above indicates a complex origin for the inter-stratified sequence at Weybourne Town Pit. Of the 11 units identified, 9 are diamictons and these are attributable to 2 lithofacies: Lithofacies C and D. The parent materials of these lithofacies are the Middle Pleistocene Bacton Green and Weybourne Town Till members of Hamblin *et al.* (2005), respectively. The remaining 2 units are represented by 2 lithofacies: a basal marl and silty sand.

Clast lithological analysis and palynomorph contents of the till lithofacies suggest that the ice responsible for the initial derivation of these tills flowed southwards from northern Britain along the east coast of England and the western margin of the North Sea (Figure 4) before entering the Weybourne region of north Norfolk. Lithological differences between the two tills reflect differential incorporation of locally-derived chalk and sand substrata.

A northerly origin for the ice responsible for the initial deposition of the Bacton Green and Weybourne Town Till members is consistent with the findings of Perrin *et al.* (1979), Fish and Whiteman (2001), Pawley *et al.* (2004) and Scheib *et al.* (in press) who investigated the Middle Pleistocene chalky tills seen in north Norfolk. Structural evidence presented in Fish *et al.* (2000) and in Hart (2007) implies a southwesterly origin for both tills. However, this relies upon the interpretation of the inter-stratified units as folds and laminations which is unlikely given the pre-dominance of brittle deformation structures. The provenance gained from this structural evidence also contrasts with a northerly provenance demonstrated by lithological and clast fabric analysis in Fish *et al.* (2000).

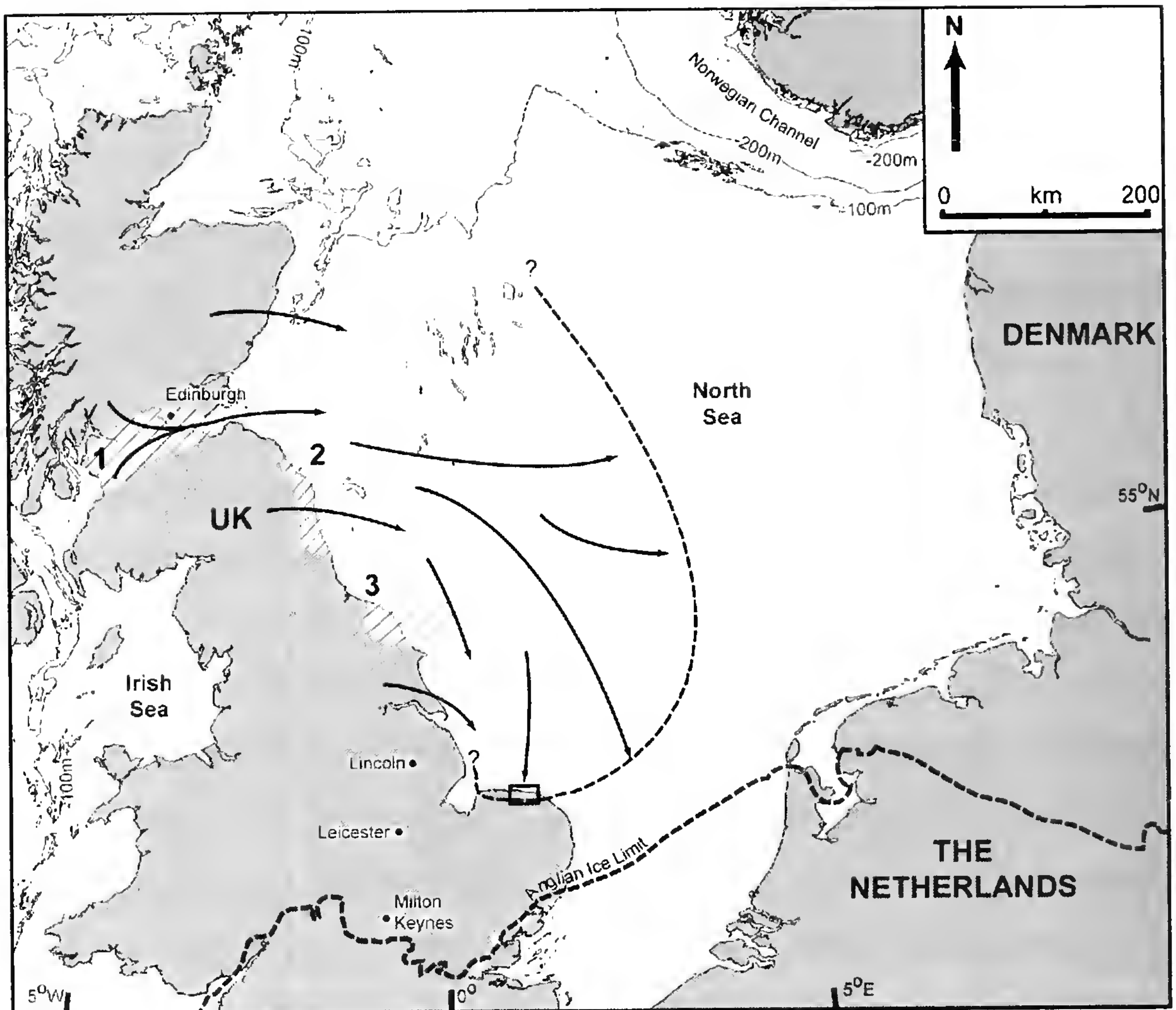

Figure 4. Ice flow model for the British Ice Sheet during accretion of the Weybourne Town Pit sequence. Source areas: 1=Midland Valley of Scotland, 2=County Durham and 3=Yorkshire Basin. Middle Pleistocene (Anglian) ice limit after Bowen *et al.* (1986) and ice lobe limit from Lee *et al.* (2002).

Interestingly, Ehlers *et al.*(1987) and Fish and Whiteman (2001) identify two divisions of chalky till within North Norfolk and suggest that these are equivalent to the Weybourne Town Till Member of Hamblin *et al.* (2005). The older of these units is believed to have been derived from a more westerly direction, whilst the sedimentology and provenance of the younger correspond closely with that of the Weybourne Town Till Member at Weybourne Town Pit presented in this study. As there is no evidence for the older unit at the pit and the pit is regarded as the type site for the Weybourne Town Till Member, the older unit should not be regarded as part of this member. This should be the case even if the entire sequence exposed at the pit (including Unit 1) has been thrust-stacked and the possibility, therefore, that the older chalky till exists at this site but below the base of the exposure.

Instead, the older unit may well correspond to the Bacton Green Till Mélange Member of Phillips *et al.* (2008). This contains material derived from the sandy Bacton Green Till Member as well as a significant proportion of glaciotectonised pre-existing sediments, including the Chalk-rich Walcott and Happisburgh Till Members (Lowestoft and Happisburgh formations, respectively) which can give the unit a Chalk-rich character. Further investigation is required before the unit can be assigned to the Bacton Green Till Mélange Member or a separate chalk-rich formation.

The presence of distinctive British clast lithologies within Lithofacies C and D and the absence of diagnostic Scandinavian erratics suggests that the Bacton Green and Weybourne Town Till members were deposited by the British Ice Sheet only. This contrasts with the view that coeval British and Scandinavian ice sheets were responsible for the deposition of the chalky and sandy tills within the area (Perrin *et al.*, 1979; Bowen *et al.*, 1986; Ehlers & Gibbard, 1991; Lunkka, 1994).

Thrust-stacking, polyphase glaciotectonic deformation and inter-stratified till sequences

The cross-cutting relationships between units 2-11, truncation of the internal fabric by adjacent disconformities and repetitive stratigraphy indicate a tectonic rather than sedimentary origin for the geometric arrangement of the silty sand and Bacton Green and Weybourne Town Till member units exposed at Weybourne Town Pit. This suggests that a sedimentary melt-out origin for inter-stratified till sequences (Haldorsen and Shaw, 1982; 1983) is not relevant in the context of Weybourne Town Pit.

Hart (2007) and Fish *et al.* (2000) interpreted the contorted Weybourne Town Pit sequence as a series of drag folds and boudins originating from ductile deforming bed conditions. However, the sharp, cross-cutting nature of the unit contacts implies that these structures are, in fact, related to brittle deformation. In addition, these brittle deformation structures truncate the internal ductile fabric of the units. The inter-stratified nature of the sequence, therefore, results from a phase of glacitectonics which postdates the primary deposition of the sediments as subaqueous sand and subglacial tills.

Dip angles and azimuth directions obtained from the sharp, persistent unit discontinuities reveal a dip at shallow angles towards the northwest, north and northeast. The geometry and structure of these discontinuities is typical of low-angle

thrust planes. The individual units are, therefore, interpreted as thrusted blocks and are seen to have formed during a series of thrusting events which stacked a unit of silty sand and alternate units of the Bacton Green Till and Weybourne Town Till members. The stress responsible for this thrust-stacking relates to ice movement from a northerly direction.

The emplacement of these inter-stratified units by different advances or multiple lobes of the same ice sheet (Straw, 1965; Perrin *et al.*, 1979; Ehlers *et al.*, 1987, 1991; Hamblin *et al.*, 2005) is unlikely. This is due to the low preservation potential of such features when formed up-ice of the maximum ice sheet extent during the advance phase of the ice sheet. The inter-stratified nature of units 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11 is, therefore, more likely to be related to short-lived oscillations of the ice margin (Fig 5) as the Middle Pleistocene ice sheet retreated from its maximum extent, marked by the Cromer Ridge. Indeed, similar glacitectonic features identified at Drymen, Scotland have been attributed to polyphase deformation resulting from an oscillating ice margin following the Loch Lomond Re-advance (Phillips *et al.*, 2002).

An ice marginal situation of the Weybourne Town Pit site during the formation of the till units is further supported by the fact that the inter-stratified sequence is relatively localised. Indeed, similar structures are absent from coastal sections between West Runton and Weybourne (Phillips *et al.*, 2008). In this context, the thrusted sequence forms part of a localised sediment stack constructed during temporary re-advances of the ice margin. In contrast, the coastal sections at West Runton and Weybourne were not subjected to glacitectonic deformation during short-lived ice marginal oscillation: instead the Middle Pleistocene ice sheet retreated relatively uniformly over these coastal locations.

The inter-stratified nature of the sequence at Weybourne Town Pit, therefore, relates to a secondary phase of deformation which post-dates the initial deposition of the Bacton Green and Weybourne Town Till members as subglacial tills of the British Ice Sheet. Active retreat of the Middle Pleistocene ice sheet would provide a possible mechanism for such localised, repetitive oscillation of the ice margin. Comparable repeated ice marginal oscillation has been noted for the retreat phase of the Late Devensian Irish Sea Ice Stream (Thomas and Chiverrell, 2007).

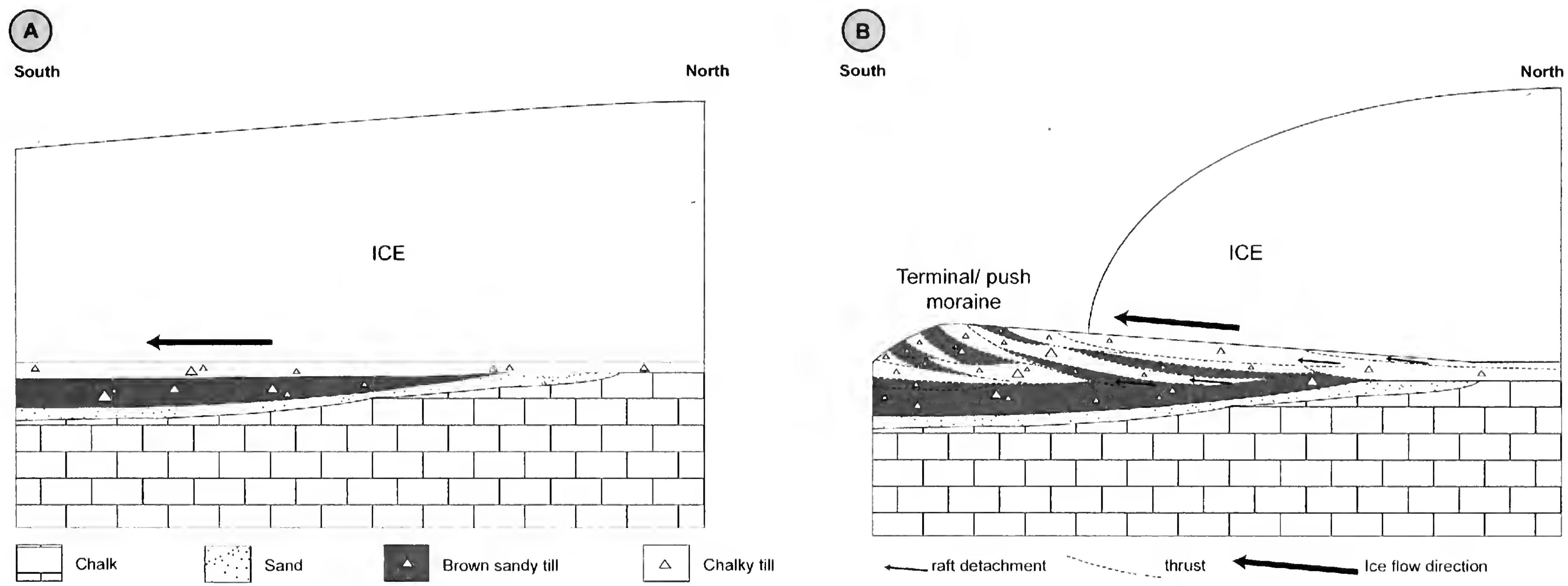

Figure 5. A thrust-stacked origin for the inter-stratified sequence at Weybourn Town Pit, North Norfolk, UK. (A) generation of the Bacton Green and Weybourn Town Till members from sand and Chalk substrata, respectively and (B) detachment, transport and emplacement of till blocks along low-angle thrust planes during active retreat of the Middle Pleistocene (Anglian) ice margin.

The palaeoenvironment of the Weybourne Town Pit sediments is, therefore, reconstructed as follows:

1. Deposition of Lithofacies A marl within a shallow lacustrine basin.
2. Deposition of Lithofacies B sand subaqueously.
3. Deposition of Lithofacies C and D subglacial tills by the Middle Pleistocene British Ice Sheet (primary deposition phase). These tills were derived by ice travelling southwards from northern Britain along the east coast of England and western margin of the North Sea.
4. Over-riding and re-mobilisation of blocks of Lithofacies B, C and D along thrust planes during short-lived, repeated oscillations of the southeast margin of the Middle Pleistocene British Ice Sheet (secondary reworking phase). This occurred during active retreat of the ice sheet from its maximum extent against the Cromer Ridge.

CONCLUSIONS

Subglacial processes play a highly significant role in controlling the behaviour of ice masses. Despite this, the processes leading to the formation and emplacement of inter-stratified sequences of subglacial tills remain particularly poorly understood. Those of the Weybourne area of north Norfolk, UK have a long history of investigation but the mechanism for the formation of the inter-stratified till sequence at Weybourne Town Pit and the direction of ice advance responsible remain particularly enigmatic. In order to address this, the current study combined lithological, structural and palynological evidence to present a re-interpretation of the sequence. Eleven units, divisible into four lithofacies were identified. These lithofacies correspond to a basal marl, silty sand and two subglacial tills of the Middle Pleistocene British Ice Sheet: the Bacton Green Till and the Weybourne Town Till members. These tills were originally derived from northern Britain by ice flowing along the east coast of England. Structural relationships between the units imply that the inter-stratified nature of the till and silty sand units results from repeated, brittle glacitectonic deformation occurring after the initial formation of these lithofacies. The style and trend of this deformation phase is consistent with accretion by a complex series of thrust-stacking events. The absence of similar structures at nearby coastal sections suggests that the effects of this glaciotectonism were highly localised, with the contorted sequence at Weybourne Town Pit related to repeated ice-marginal

oscillation during the active retreat of the Middle Pleistocene British Ice Sheet from its maximum extent against the Cromer Ridge.

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REFERENCES

BADEN-POWELL, D.F.W. 1948. The Chalky Boulder Clays of Norfolk and Suffolk. *Geological Magazine,* **85**, 279-296.

BANHAM, P.H. & RANSON, C.E. 1956. Structural Study of the Contorted Drift and Disturbed Chalk at Weybourne, North Norfolk. *Geological Magazine*, **102**, 164-174.

BENTLEY, C.R. 1997. Rapid sea-level rise soon from West Antarctic ice sheet collapse? *Science*, **275**, 1077-1078.

BOWEN, D.Q., ROSE, J., MCCABE, A.M. & SUTHERLAND, D.G., 1986. *Quaternary Deposits in the British Isles*. Geological Survey of London Special Report No. 23.

BUCEFALO PALLIANI, R. & RIDING, J.B. 2003. Biostratigraphy, provincialism and evolution of European Early Jurassic (Pliensbachian to early Toarcian) dinoflagellate cysts. *Palynology*, **27**, 179-214.

COX, F.C. & NICKLESS, E.F.P. 1972. Some aspects of the glacial history of central Norfolk. Bulletin of the Geological Survey of Great Britain, **42**, 79-98.

EHLERS, J. & GIBBARD, P. 1991. Anglian glacial deposits in Britain and the adjoining offshore regions. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), *Glacial deposits of Great Britain and Ireland.* Balkema, Rotterdam, pp. 17 24.

EHLERS, J., GIBBARD, P. & WHITEMAN, C.A. 1987. *Recent investigations of the Marly Drift of northwest Norfolk, England.* INQUA Symposium on the Genesis and Lithology of Glacial Deposits, Amsterdam, pp. 39-54.

EHLERS, J., GIBBARD, P. & WHITEMAN, C.A. 1991. The glacial deposits of

north-western Norfolk. In: Ehlers, J., Gibbard, P., Rose, J. (Eds.), *Glacial Deposits in Great Britain and Ireland*. Balkema, Rotterdam, pp. 223-232.

EVANS, D.J.A., PHILLIPS, E.R., HIEMSTRA, J.F. & AUTON, C.A. 2006. Subglacial till: formation, sedimentary characteristics and classification. *Earth Science Reviews*, **78**, 115-176.

FISH, P.R. & WHITEMAN, C.A. 2001. Chalk micropalaeontology and the provenancing of Middle Pleistocene Lowestoft Formation till in eastern England. *Earth Surface Processes and Landforms,* **26**, 953-970.

FISH, P.R., WHITEMAN, C.A., MOORLOCK, B.S.P., HAMBLIN, R.J.O. & WILKINSON, I.P. 2000. Weybourne, north Norfolk: a new analysis based on chalk micropalaeontology. In: Lewis, S.G., Whiteman, C.A., Preece, R.C. (Eds.), *The Quaternary of Norfolk and Suffolk: Field Guide*. Quaternary Research Association, London, pp. 119-130.

FRIELE, P. A. & CLAGUE, J. J. 2002. Younger Dryas readvance in Squamish river valley, southern Coast mountains, British Columbia. *Quaternary Science Reviews*, **21**, 1925-1933.

HALDORSEN, S. & STRAW, J. 1982. The problem of recognising melt-out till. *Boreas*, **11**, 261-277.

HAMBLIN, R.J.O., MOORLOCK, B.S.P. & ROSE, J. 2000. A new glacial stratigraphy for Eastern England. *Quaternary Newsletter*, **92**, 35-43.

HAMBLIN, R.J.O., MOORLOCK, B.S.P., ROSE, J., LEE, J.R., RIDING, J.B., BOOTH, S.J. & PAWLEY, S.M. 2005. Revised pre-Devensian glacial stratigraphy in Norfolk, England, based on mapping and till provenance. *Netherlands Journal of Geosciences/ Geologie en Mijnbouw*, **84**, 77-85.

HART, J.K. 1990. Proglacial glaciotectonic deformation and the origin of the Cromer Ridge push moraine complex, North Norfolk, England. *Boreas*, **19**, 165-180.

HART, J.K. 2007. An investigation of subglacial shear zone processes from Weybourne, Norfolk, UK. *Quaternary Science Reviews,* **26**, 2354-2374.

HART, J.K., HINDMARSH, R.C.A. & BOULTON, G.S. 1990. Styles of subglacial glaciotectonic deformation within the context of the Anglian ice-sheet. *Earth Surface Processes and Landforms*, **15**, 227-241.

HUGHES, T. 1996. Can ice sheets trigger abrupt climate change? *Arctic and Alpine Research*, **28**, 448-465.

LEE, J.R., ROSE, J., RIDING, J.B., MOORLOCK, B.S.P. & HAMBLIN, R.J.O.

2002. Testing the case for a Middle Pleistocene Scandinavian glaciation in Eastern England: evidence for a Scottish ice source for tills within the Corton Formation of East Anglia, UK. *Boreas*, **31**, 345-355.

LEE, J.R., 2003. *Early and Middle Pleistocene lithostratigraphy and palaeoenvironments in northern East Anglia, UK.* Unpublished PhD Thesis, Royal Holloway University of London.

LEE, J.R., BOOTH, S.J., HAMBLIN, R.J.O., JARROW, A.M., KESSLER, H., MOORLOCK, B.S.P., MORIGI, A.N., PALMER, A., PAWLEY, S.J., RIDING, J.B. & ROSE, J. 2004. A new stratigraphy for the glacial deposits around Lowestoft, Great Yarmouth, North Walsham and Cromer, East Anglia, UK. *Bulletin of the Geological Society of Norfolk*, **53**, 3-60.

LEE, J.R., PAWLEY, S.M., ROSE, J., MOORLOCK, B.S.P., RIDING, J.B., HAMBLIN, R.J.O., CANDY, I., BARENDREGT, R.W., BOOTH, S.J. & HARRISON, A.M. 2008. Pre-Devensian lithostratigraphy of shallow marine, fluvial and glacial sediments in northern East Anglia. In: Candy, I., Lee, J.R., Harrison, A.M. (Eds.), *The Quaternary of northern East Anglia: Field Guide.* Quaternary Research Association, London, pp. 42-59.

LUNKKA, J.P. 1994. Sedimentation and lithostratigraphy of the North Sea Drift and Lowestoft Till Formations in the coastal cliffs of northeast Norfolk, England. *Journal of Quaternary Science*, **9**, 209-233.

MENZIES, J. & ELLWANGER, D. 2011. Insights into subglacial processes inferred from the micromorphological analyses of complex diamicton stratigraphy near Illmensee-Lichtenegg, Höchsten, Germany. *Boreas,* **40**, 271-288.

MENZIES, J., VAN DER MEER, J.J.M. & ROSE, J. 2006. Till-as a glacial 'tectomict', its internal architecture, and the development of a 'typing' method for till differentiation. Geomorphology, **75**, 172-200.

PAWLEY, S.M., ROSE, J., LEE, J.R., MOORLOCK, B.S.P. & HAMBLIN, R.J.O. 2004. Middle Pleistocene sedimentology and lithostratigraphy of Weybourne, northeast Norfolk, England. *Proceedings of the Geologists' Association*, **115**, 25-42.

PAWLEY, S.M., LEE, J.R., RIDING, J.B., MOORLOCK, B.S.P., HAMBLIN, R.J.O., ROSE, J. & CROFTS, R.G. 2005. The stratigraphy of the Briton's Lane borehole and quarry, Beeston Regis, north-east Norfolk. *Bulletin of the Geological Society of Norfolk*, **55**, 15-41.

PAWLEY, S. M., CANDY, I. & BOOTH, S. J. 2006. The Late Devensian terminal moraine ridge at Garret Hill, Stiffkey valley, north Norfolk, England. *Proceedings of the Yorkshire Geological Society*, **56**, 31-39.

PERRIN, R.M.S., ROSE, J. & DAVIES, H. 1979. The distribution, variation and origins of pre-Devensian tills in eastern England. *Philosophical Transactions of the Royal Society of London*, **287** (1024), 535-570.

PHILLIPS, E., EVANS, D.J.A. & AUTON, C.A. 2002. Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. *Sedimentary Geology*, **149**, 157-182.

PHILLIPS, E., LEE, J.R. & BURKE, H.K. 2008. Progressive proglacial to subglacial deformation and syntectonic deformation at the margins of the Mid Pleistocene British Ice Sheet: evidence from north Norfolk, UK. *Quaternary Science Reviews*, **27**, 1848-1871.

POWELL, A.J. 1992. Dinoflagellate cysts of the Tertiary system. In: Powell, A.J. (Ed.), *A stratigraphic index of dinoflagellate cysts*. British Micropalaeontological Society Publications Series. Chapman and Hall, London, pp. 155-251.

RIDING, J.B. & THOMAS, J.E. 1992. Dinoflagellate cysts of the Jurassic System. In: Powell, A.J. (Ed.), *A stratigraphic index of dinoflagellate cysts*. British Micropalaeontological Society Publications Series. Chapman and Hall, London, pp. 7-97.

RIDING, J.B. & KYFFIN-HUGHES, J.E. 2004. A review of the laboratory preparation of palynomorphs with a description of an effective non-acid technique. *Revista Brasileira de Paleontologia,* **7** (1), 13-44.

RIDING, J.B. & KYFFIN-HUGHES, J.E. 2006. Further testing of a non-acid palynological preparation procedure. *Palynology*, **30**, 69-87.

RIDING, J.B., ROSE, J. & BOOTH, S.J. 2003. Allochthonous and indigenous palynomorphs from the Devensian of the Warham Borehole, Stiffkey, north Norfolk, England: evidence for sediment provenance. *Proceedings of the Yorkshire Geological Society*, **54**, 223-235.

ROSE, J. 2008. Palaeogeography of Eastern England during the Early and Middle Pleistocene. In: Candy, I., Lee, J.R., Harrison, A.M. (Eds.), *The Quaternary of northern East Anglia: Field Guide*. Quaternary Research Association, London, pp.5-41.

ROSE, J. 2009. Early and Middle Pleistocene landscapes of eastern England. *Proceedings of the Geologists' Association*, **120** (1), 3-33.

SCHEIB, A.J., LEE, J.R., BREWARD, N. & RIDING, J.B. in press. Reconstructing flow paths of the Middle Pleistocene British Ice Sheet in central-eastern England: the application of regional soil geochemical data. *Proceedings of the Geologists' Association,* doi:10.1016/j.pgeola.2011.01.008.

SHAW, J. 1982. Melt-out till in the Edmonton area, Alberta, Canada. Canadian *Journal of Earth Sciences*, **19**, 1548-1569.

SHAW, J. 1983. Forms associated with boulders in melt-out till. In: Everson, E.B., Schluchter, C., Rose, J. (Eds.), *Tills and Related Deposits.* Balkema, Rotterdam, pp. 3-12.

STRAW, A. 1965. A Reassessment of the Chalky Boulder Clay or Marly Drift of North Norfolk. *Zeitschrift für Geomorphologie*, **2**, 209-221.

THOMAS, G.S.P & CHIVERRELL, R.C. 2007. Structural and depositional evidence for repeated ice-marginal oscillation along the eastern margin of the Late Devensian Irish Sea Ice Stream. *Quaternary Science Reviews*, **26**, 2375-2405.

VAN DER MEER, J.J.M., MENZIES, J. & ROSE, J. 2003. Subglacial till: the deforming glacier bed. *Quaternary Science Reviews*, **22**, 1659-1685.

WOOD, G.D., GABRIEL, A.M. & LAWSON, J.C. 1996. Chapter 3. Palynological techniques-processing and microscopy. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: principles and applications.* American Association of Stratigraphic Palynologists Foundation, Dallas, pp. 29-50.

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The Geological Society of Norfolk exists to promote the study and understanding of geology in East Anglia, and holds meetings throughout the year. For further details consult our Web Site (http://www.norfolkgeology.co.uk) or write to Dr David Waterhouse, Secretary of the Geological Society of Norfolk, Assistant Curator of Natural History (Acting Curator of Geology), Norfolk Museums Service, The Shirehall, Market Avenue, Norwich, NR1 3JQ.

Copies of the Bulletin (including older back copies) can be obtained from the editor at the address on p.1; it is issued free to members.

The illustration on the front cover is figure 5b from the article by Evans et al. in this issue of the Bulletin. It shows a conceptual model for detachment, transport and emplacement of blocks along low-angle thrust planes during retreat of the Anglian ice margin in north Norfolk.

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